AN ECOLOGICAL APPROACH TO CLIMATE AND CLIMATE CHANGE

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viewgraphs available at www.ecd.bnl.gov/steve

ECOLOGY – THE STUDY OF THE HOUSE

The scientific study of the relations that living organisms have with respect to each other and their environment

The scientific study of the relations among the components of the climate system that govern the overall climate

THE ECOLOGICAL APPROACH

Identify key variables and adduce simple relations governing their evolution

Variables:

- Number, mass age distribution, by species or classes of species
- Resource requirements per individual
- Resource availability
- Predation rate (species interactions)

Approach:

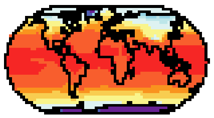
- Identify rules
- Express in terms of differential equations

Output:

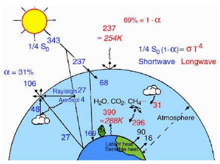
- Predictive capability
- Ability to project with confidence the consequences of various external perturbations

OVERVIEW

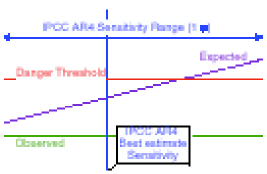
? ? ? Some simple questions about climate change



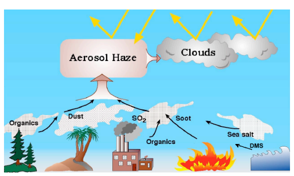
First principles climate modeling



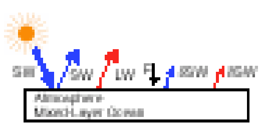
Earth's energy balance and perturbations



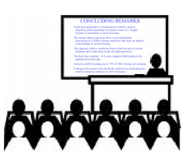
Climate system response and the warming discrepancy



Aerosol forcing – uncertainty and implications



Global energy balance models



Summary and conclusions

SOME SIMPLE QUESTIONS ABOUT CLIMATE CHANGE

How much has ***Global Mean Surface Temperature*** (GMST) increased over the industrial period?

What is the magnitude of ***forcing*** over the industrial period?

What is Earth's ***climate sensitivity***?

What is the expected ***equilibrium increase*** in GMST?

Why hasn't GMST increased as much as expected?

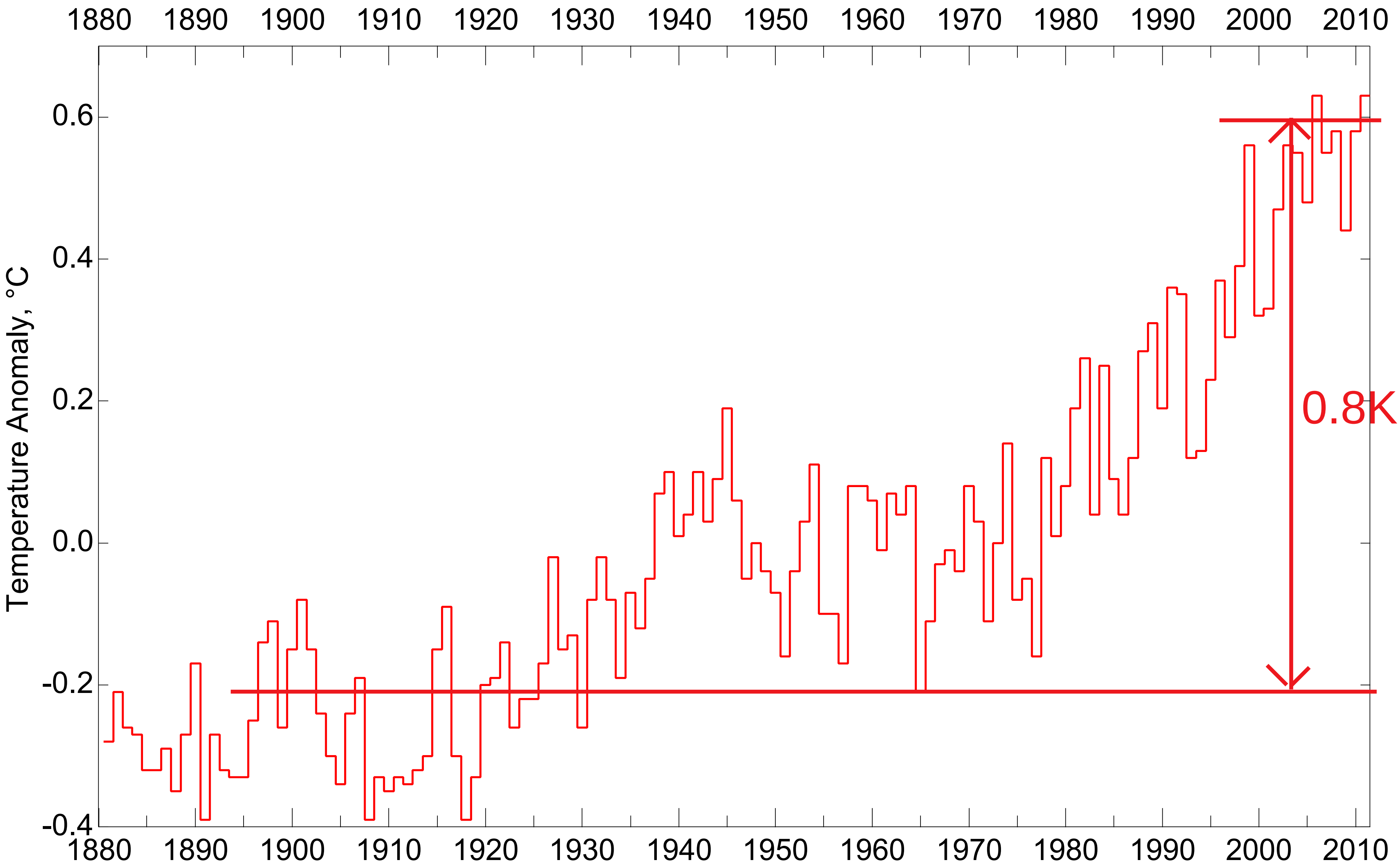
How much of this is due to ***time lag of response*** of the climate system? What are the ***time constants*** of the system?

How much is due to ***offsetting forcing by tropospheric aerosols***?

What is the magnitude of the ***planetary energy imbalance***?

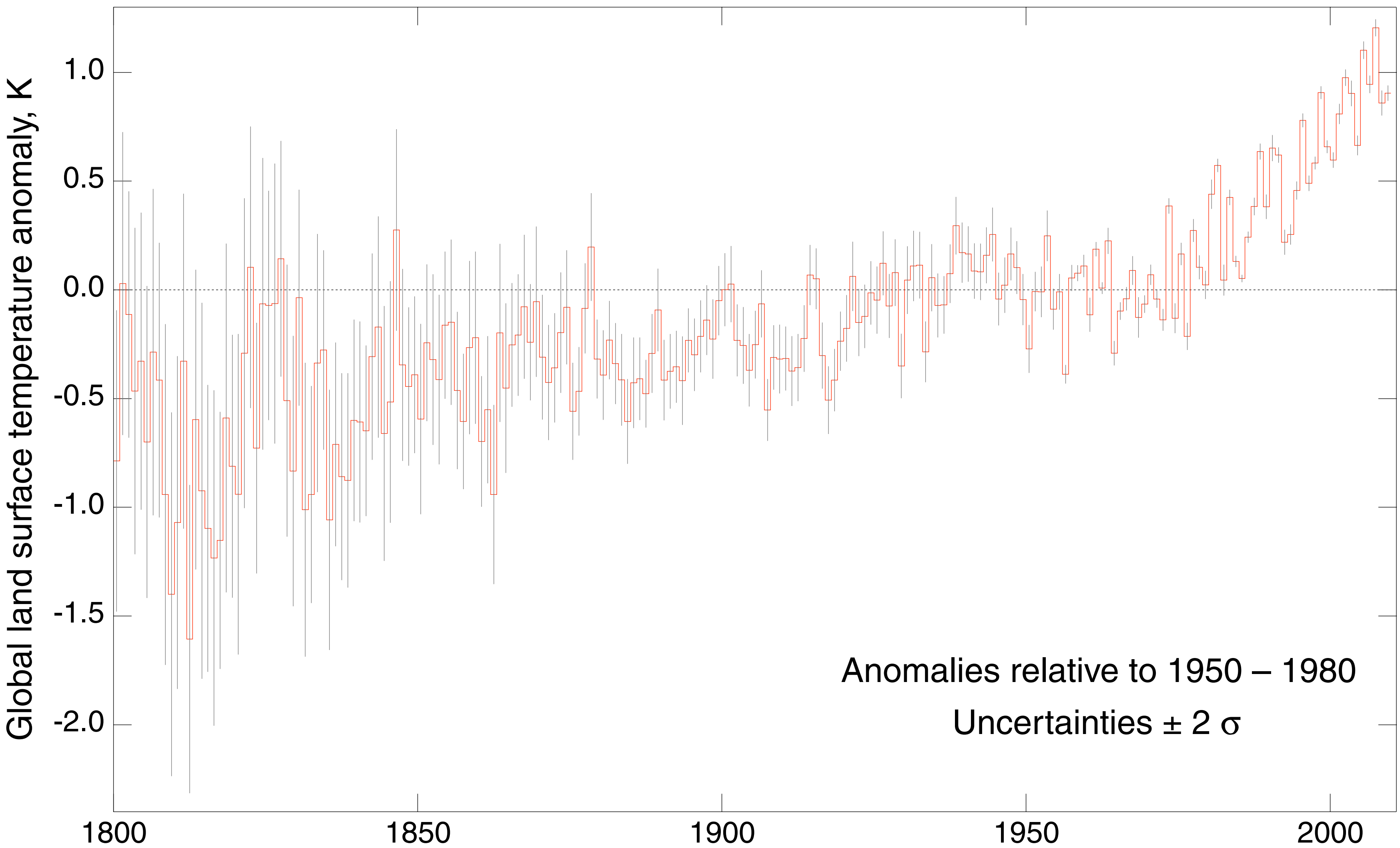
How much more warming is "***in the pipeline***" – committed warming?

GLOBAL ANNUAL TEMPERATURE ANOMALY, 1880-2010



Data: Goddard Institute for Space Studies

GLOBAL LAND SURFACE TEMPERATURE ANOMALY



Muller et al. (Berkeley Earth Project), submitted, 2011

Independent analysis confirms increase in temperature over 20^{th} century.

APPROACHES TO DEVELOPING PREDICTIVE CAPABILITY FOR CLIMATE CHANGE

First principles climate modeling

Perturbation models

FIRST PRINCIPLES CLIMATE MODELING

Approach

Understand the processes controlling climate and climate change.

Represent these explicitly in computer models.

Improve resolution (spatial, process) until the model provides a sufficiently accurate representation.

Evaluate model by comparison with observations.

Product

Predictive capability; ability to project the ***many consequences*** of various hypothetical external perturbations – not just GMST.

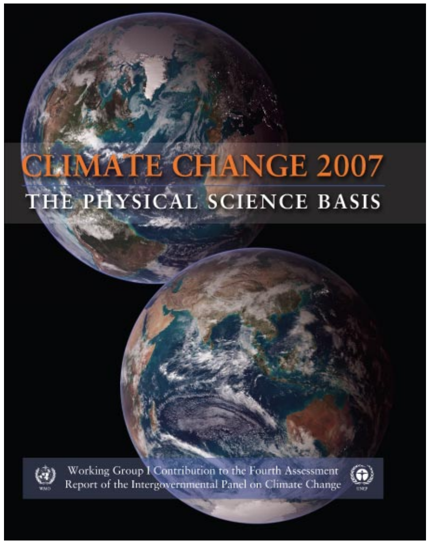
Modeled changes in quantities of interest for various "what if?" scenarios.

Concerns

Accuracy. The model must be sufficiently accurate that the consequences of small perturbations can be determined with confidence as the ***difference with and without the perturbation***.

Sensitivity to processes that are not well understood or represented.

THE BIBLE OF CLIMATE CHANGE



It's big and thick.

Every household should have one.

No one reads it from cover to cover.

You can open it up on any page and find something interesting.

It was written by a committee.

It is full of internal contradictions.

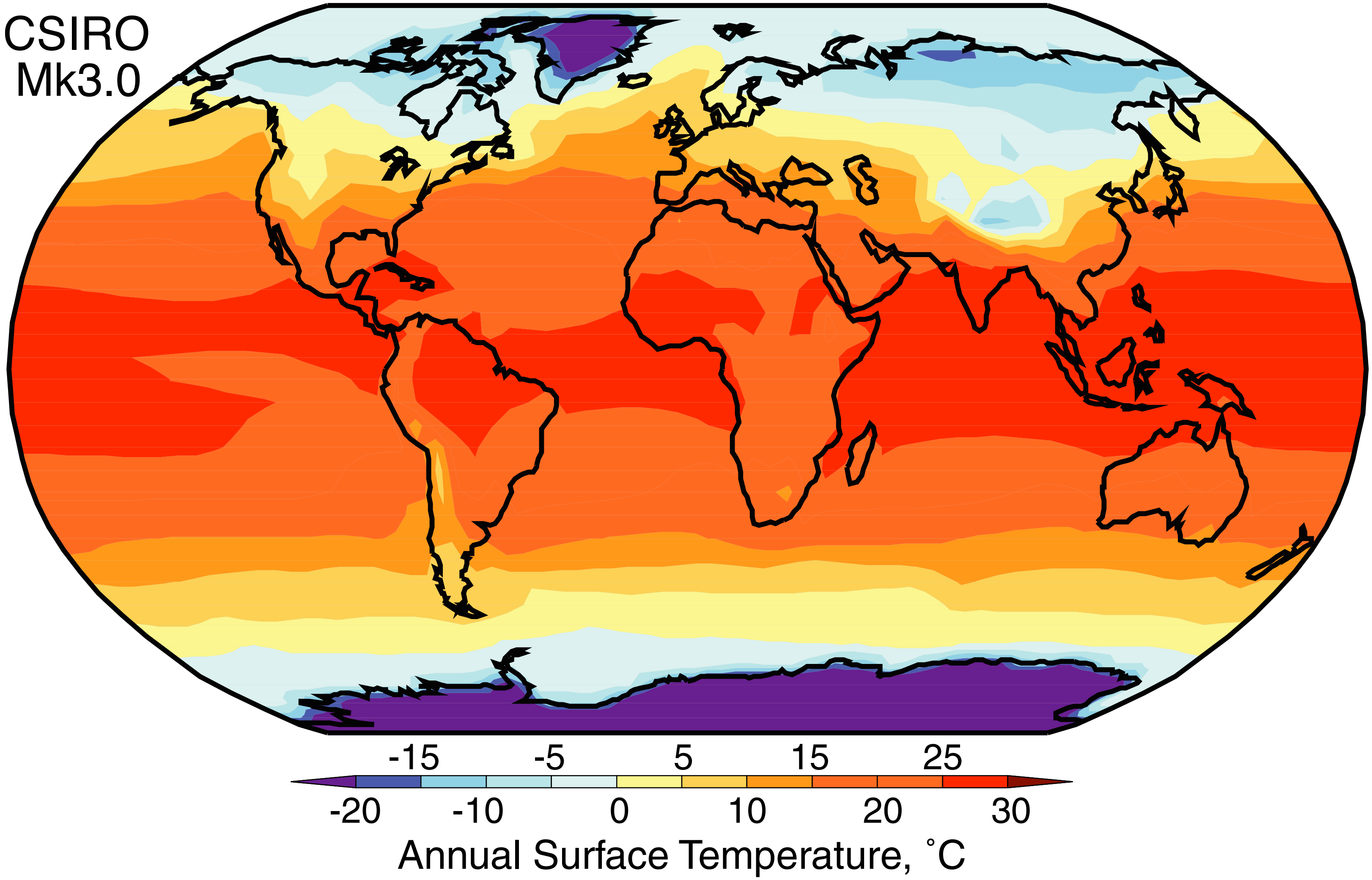
It deals with cataclysmic events such as floods and droughts.

It has its true believers and its skeptics.

It can be downloaded free from the internet.

ANNUAL MEAN SURFACE TEMPERATURE

Calculated with Global Climate Model

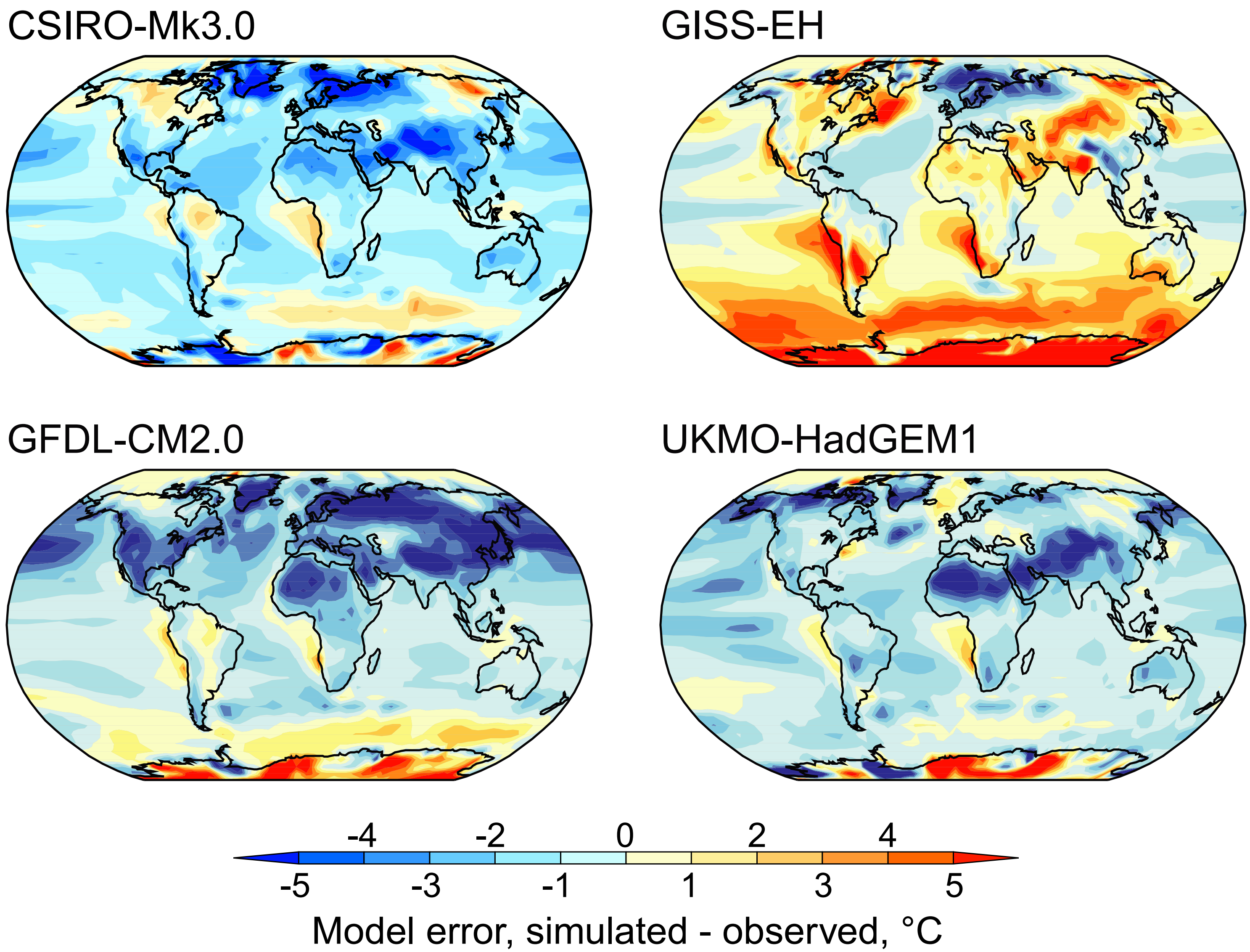


IPCC, 2007, Chapter 8, Suppl.

Model output is richly detailed. Overall pattern is quite good, given that ***the entire climate system is modeled from first principles***.

ANNUAL MEAN SURFACE TEMPERATURE

Difference from observations, calculated with Global Climate Model

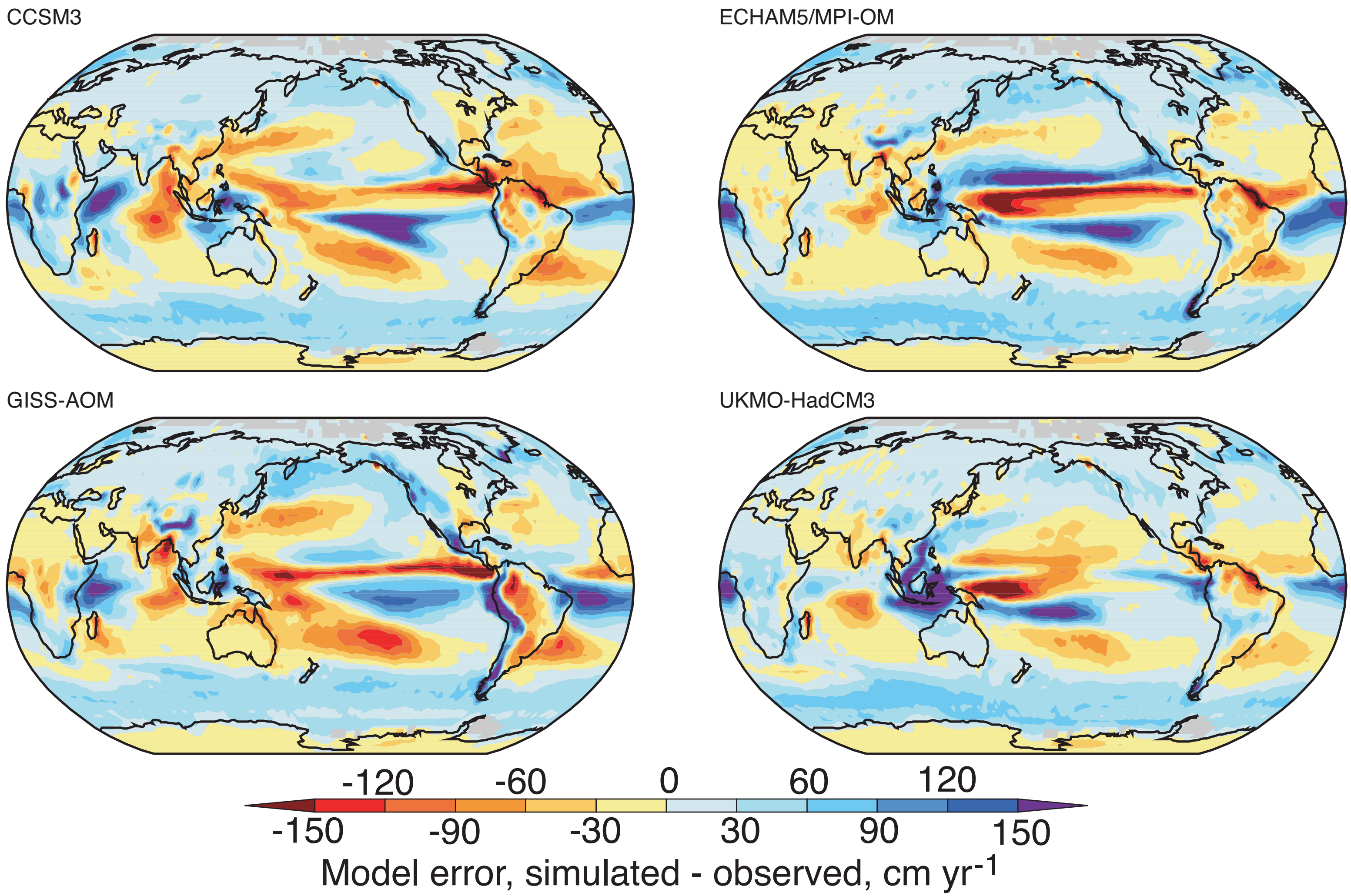


IPCC, 2007, Chapter 8, Suppl.

Accuracy is quite good as a fraction of 288 K, but differences are climatologically significant and exceed expected warming.

ANNUAL MEAN PRECIPITATION

Difference from observations, calculated with Global Climate Models

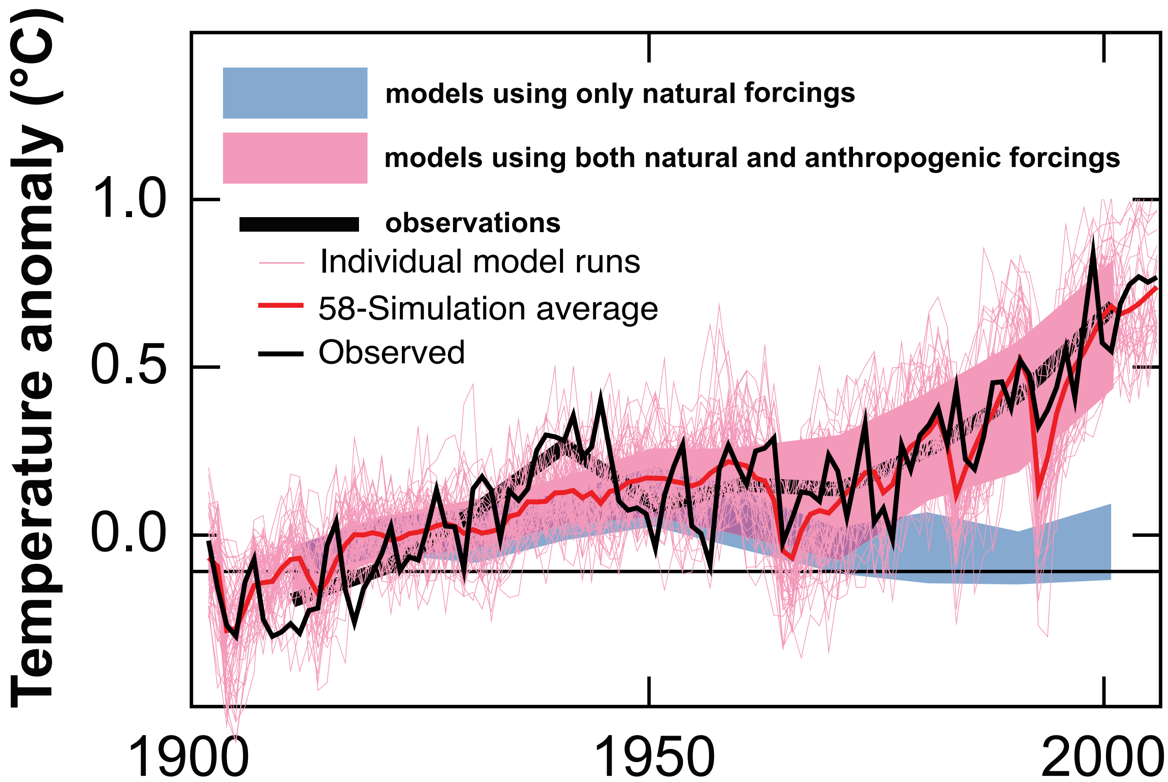


IPCC, 2007, Chapter 8, Suppl.

Departure from observations and model-to-model differences are substantial in some locations.

GLOBAL MEAN SURFACE TEMPERATURE ANOMALY OVER THE TWENTIETH CENTURY

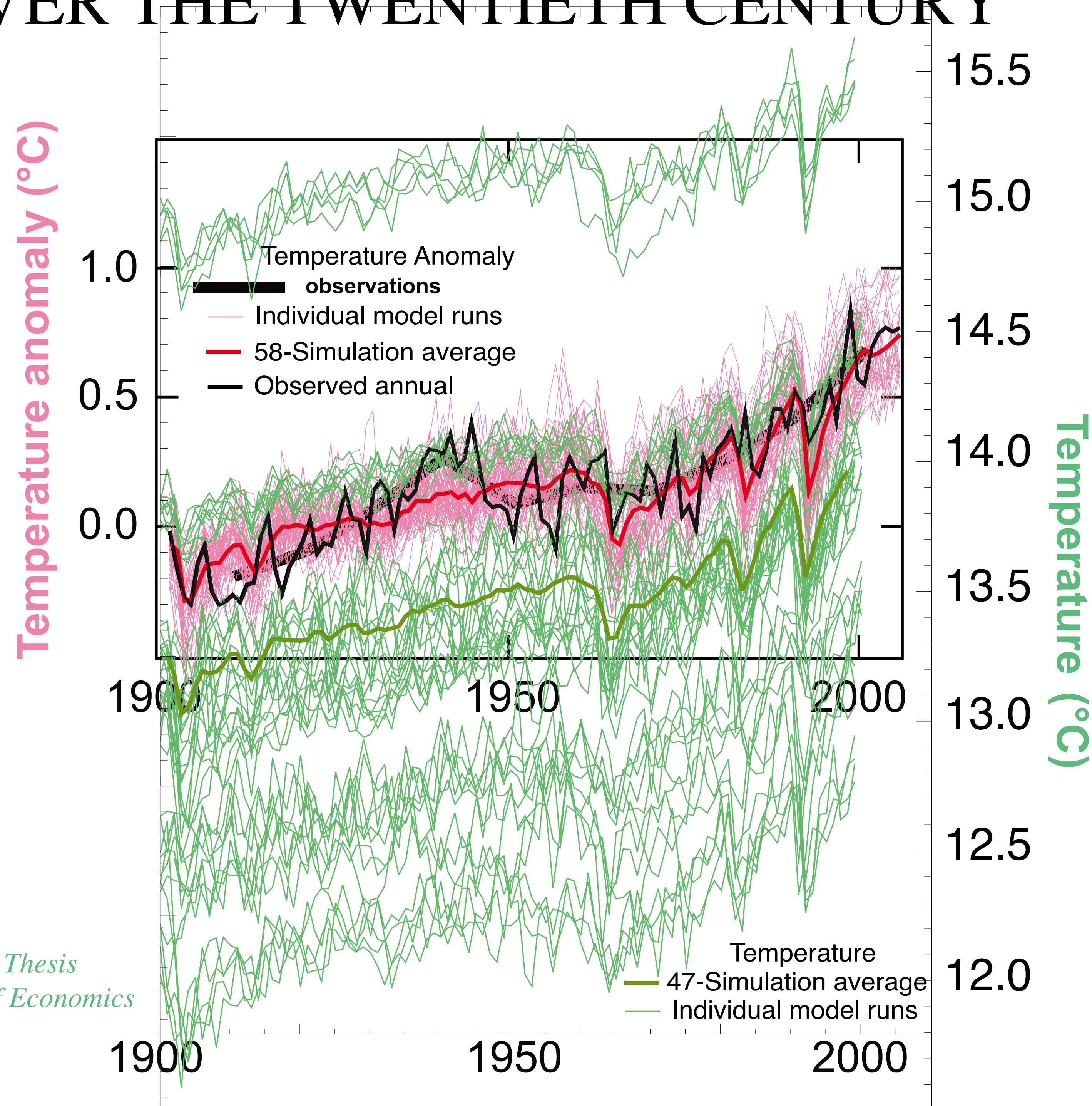
Ensemble of 58 model runs with 14 global climate models



“ Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.

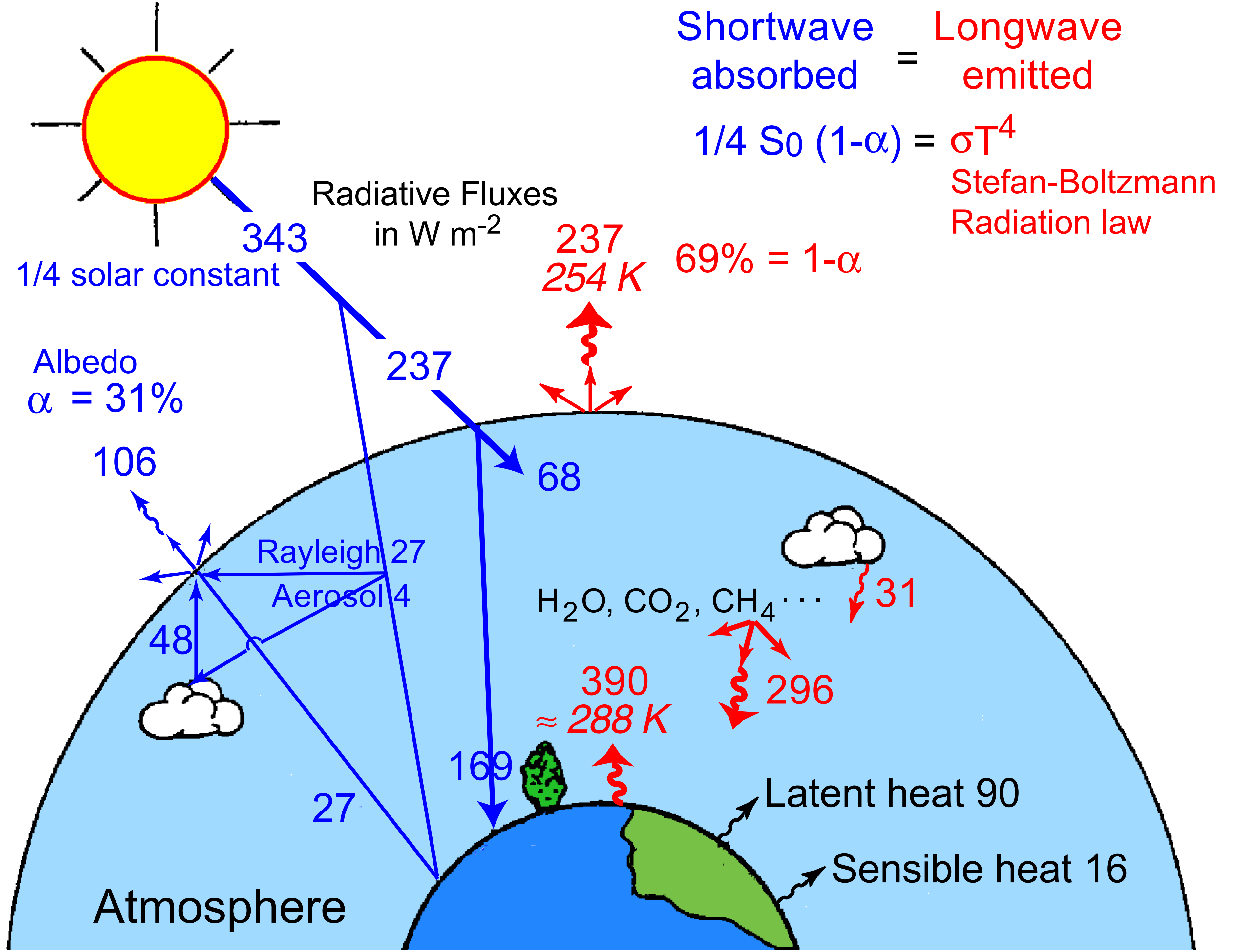
IPCC AR4, 2007

GLOBAL MEAN SURFACE TEMPERATURE OVER THE TWENTIETH CENTURY



E. Tredger, 2009, Thesis
London School of Economics

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



Modified from Schwartz, 1996; Ramanathan. 1987

RADIATIVE FORCING

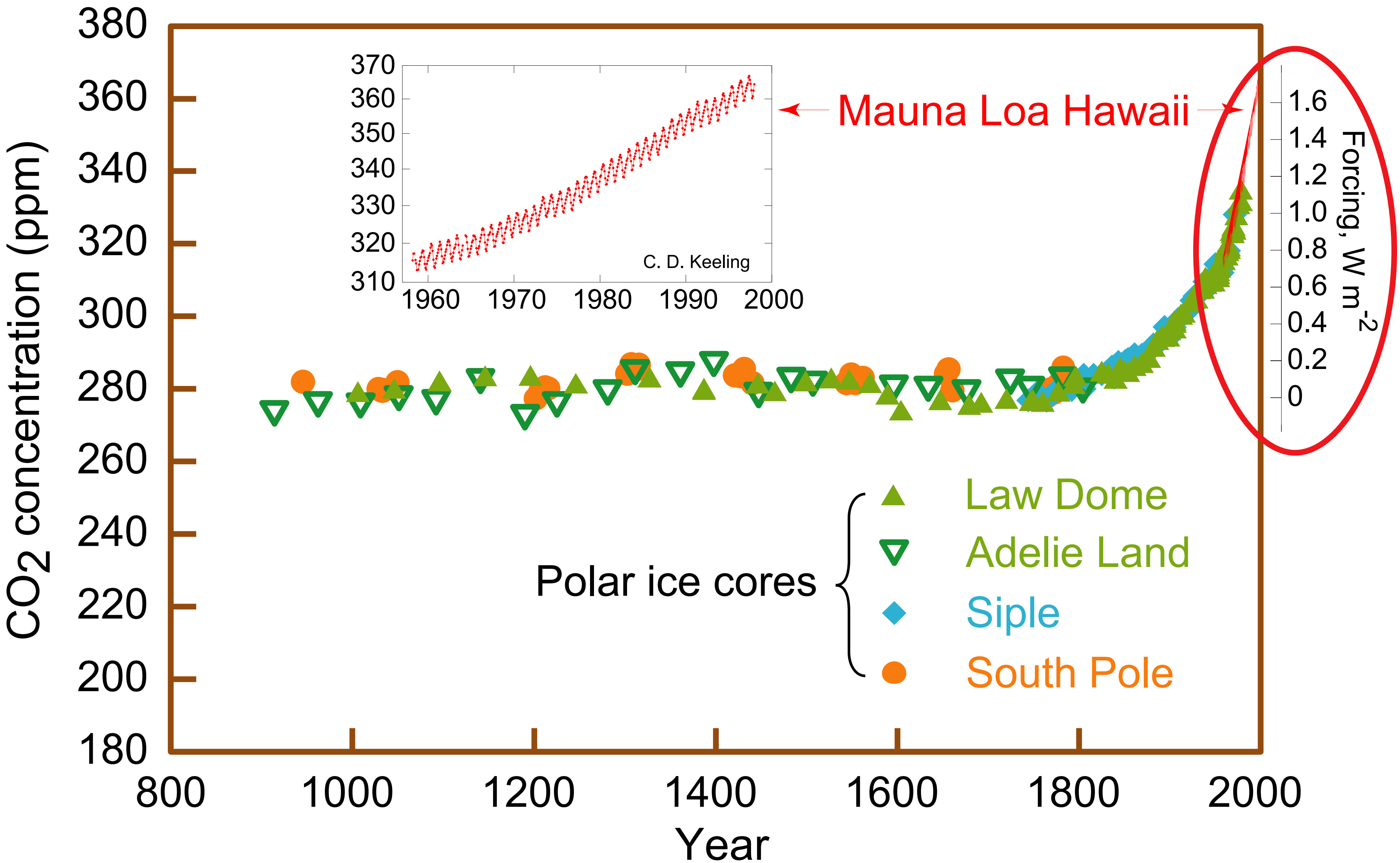
An externally imposed ***change*** in Earth's radiation budget, F, W m^{-2}.

Working hypothesis:

On a global basis radiative forcings are additive and interchangeable.

- This hypothesis is fundamental to the radiative forcing concept.
- This hypothesis underlies much of the assessment of climate change over the industrial period.

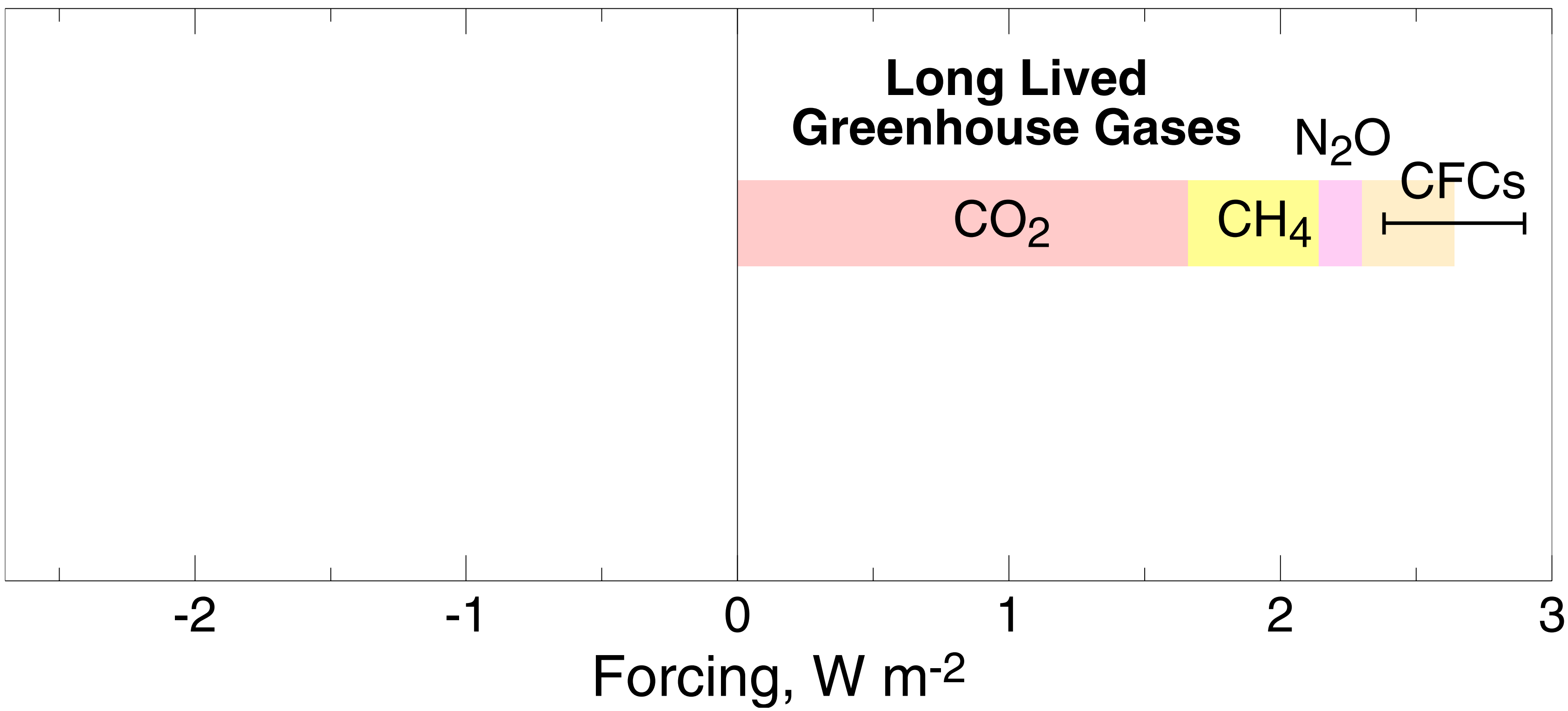
ATMOSPHERIC CARBON DIOXIDE IS INCREASING



The increase in CO_2, a greenhouse gas, has produced a radiative forcing which is now 1.7 W m^{-2}.

CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

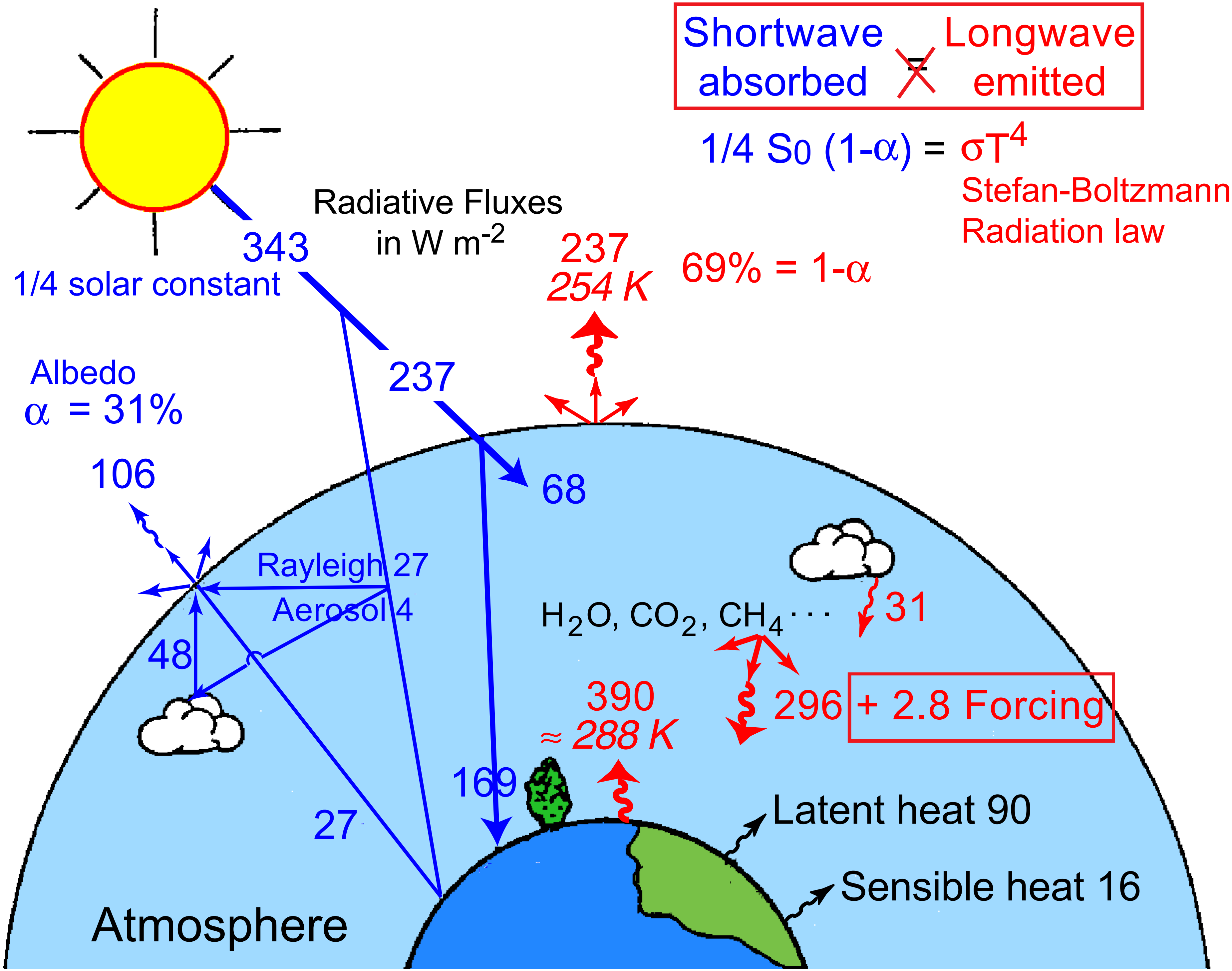
Extracted from IPCC AR4 (2007)



Gases are uniformly distributed; radiation transfer is well understood.

Greenhouse gas forcing is considered accurately known.

EARTH'S RADIATION BUDGET AND THE GREENHOUSE EFFECT



Modified from Schwartz, 1996; Ramanathan. 1987

CLIMATE SYSTEM RESPONSE

Increase in global mean surface temperature = Equilibrium climate sensitivity × Effective Forcing

$$\boxed{\Delta T = S_{eq} \times F_{eff}}$$

S_{eq} is Earth's ***equilibrium climate sensitivity***, units K / (W m^{-2})

F_{eff} is ***effective forcing***, $F_{eff} = F - dH/dt$.

dH/dt is ***planetary heating rate*** determined mainly from ocean heat content measurements, 0.8 W m^{-2}.

For increases in CO_2, CH_4, N_2O, and CFCs over the industrial period, ***forcing*** $F = 2.8$ W m^{-2}.

Effective forcing $F_{eff} = 2.0$ W m^{-2}.

CO_2 DOUBLING TEMPERATURE

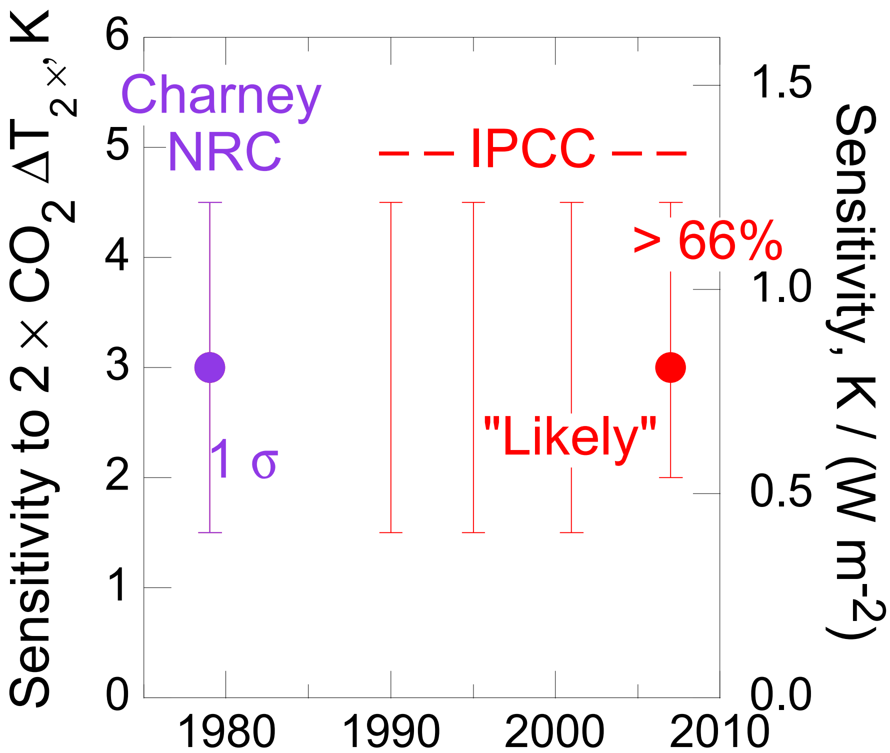
Climate sensitivity is commonly expressed as
"CO_2 doubling temperature" unit K or °C

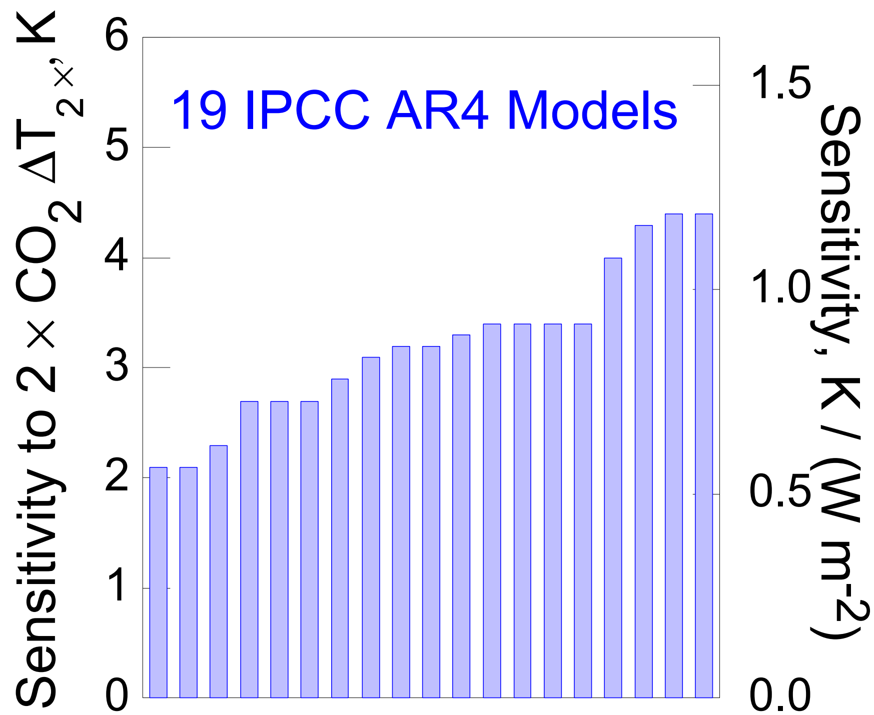
$$\boxed{\Delta T_{2\times} \equiv S_{eq} \times F_{2\times}}$$

where $F_{2\times}$ is the CO_2 doubling forcing, *ca*. 3.7 W m^{-2}.

ESTIMATES OF EARTH'S CLIMATE SENSITIVITY AND ASSOCIATED UNCERTAINTY

Major national and international assessments and current climate models





Current estimates of Earth's climate sensitivity are centered about a CO_2 doubling temperature $\Delta T_{2\times} = 3$ K, but with substantial uncertainty.

Range of sensitivities of current models roughly coincides with IPCC "likely" range.

EXPECTED WARMING

For increases in CO_2, CH_4, N_2O, and CFCs over the industrial period, ***forcing*** $F = 2.8\ \text{W m}^{-2}$,

Planetary heating rate $dH/dt = 0.8\ \text{W m}^{-2}$,

Effective forcing $F_{\text{eff}} = F - dH/dt = 2.0\ \text{W m}^{-2}$,

CO_2 doubling forcing $F_{2\times} = 3.7\ \text{W m}^{-2}$,

IPCC best estimate ***doubling temperature*** $\Delta T_{2\times} = 3\ ^{\circ}\text{C}$,

The ***expected temperature increase*** is

$$\Delta T_{\text{exp}} = \frac{F_{\text{eff}}}{F_{2\times}} \times \Delta T_{2\times} = \frac{2.0}{3.7} \times 3\ ^{\circ}\text{C} = 1.6\ ^{\circ}\text{C}$$

THE WARMING DISCREPANCY

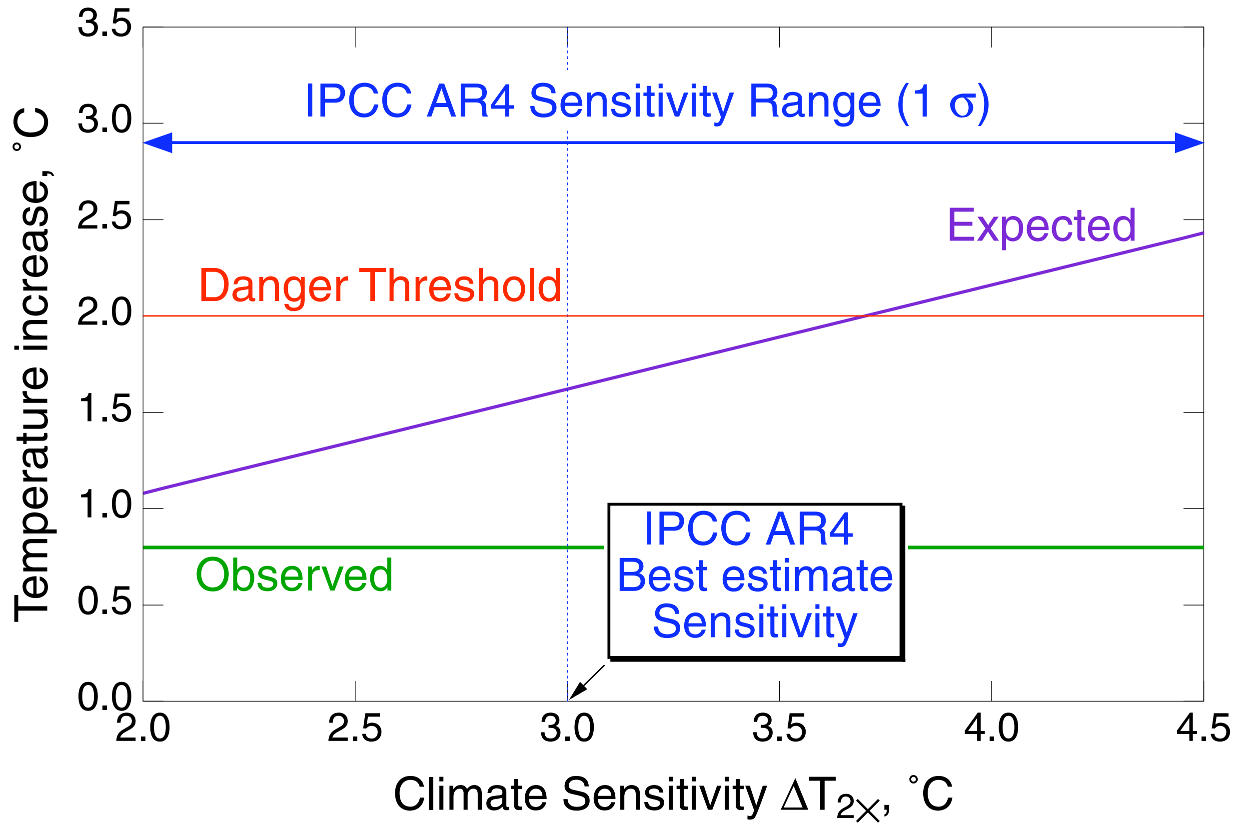
Expected temperature increase: $\Delta T_{\text{exp}} = 1.6\ ^{\circ}\text{C}$

Observed temperature increase: $\Delta T_{\text{obs}} = 0.8\ ^{\circ}\text{C}$

How can we account for this ***warming discrepancy***?

EXPECTED TEMPERATURE INCREASE

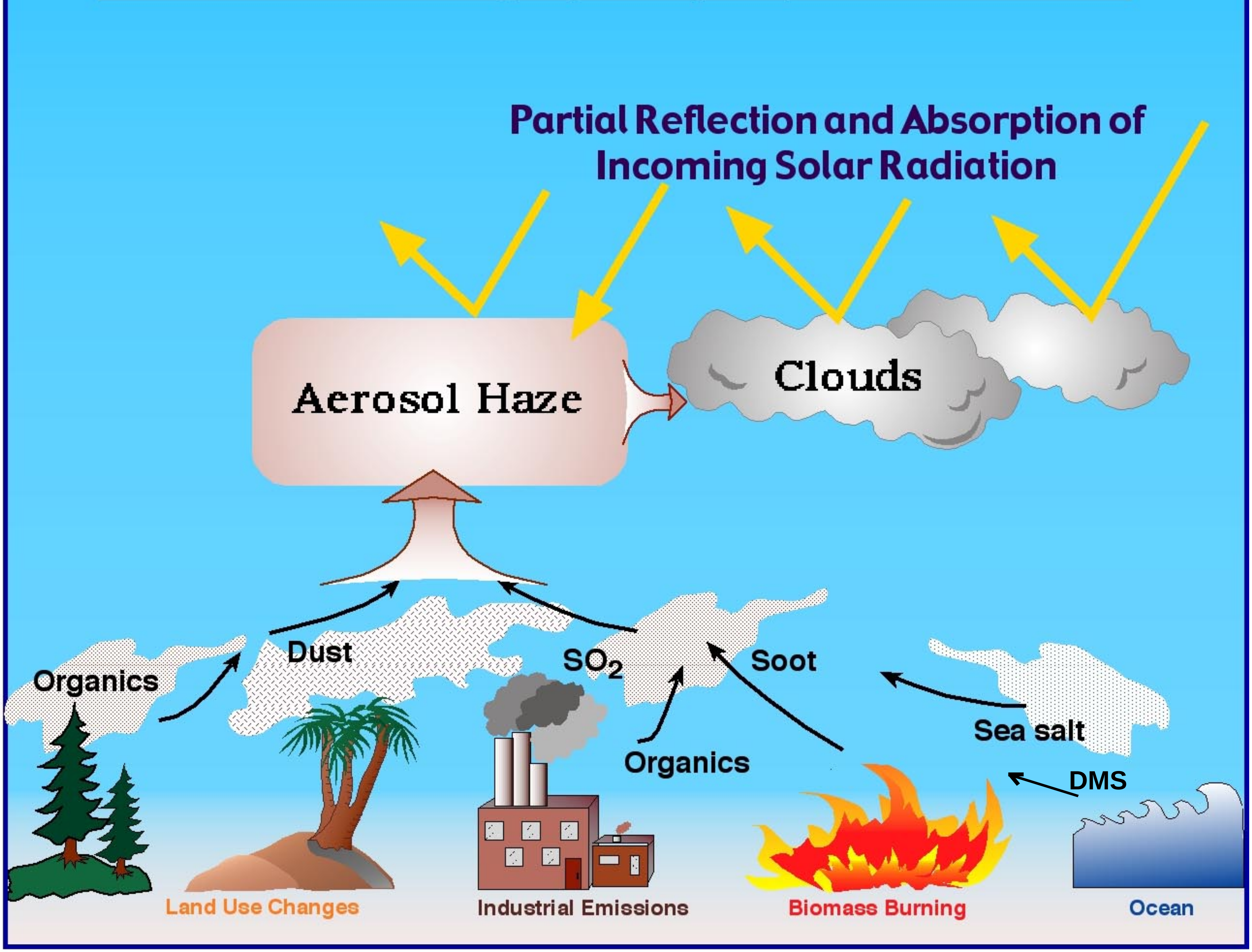
Based on greenhouse gas forcing only, 2.8 W m^{-2}, with planetary heating rate 0.8 W m^{-2} (effective forcing 2.0 W m^{-2})



Expected temperature increase exceeds observed for entire IPCC (2007) sensitivity range.

Depending on sensitivity, expected temperature increase approaches or exceeds 2˚C, widely accepted threshold for onset of dangerous anthropogenic interference with the climate system.

Radiative Forcing by Tropospheric Aerosol



AEROSOL IN MEXICO CITY BASIN

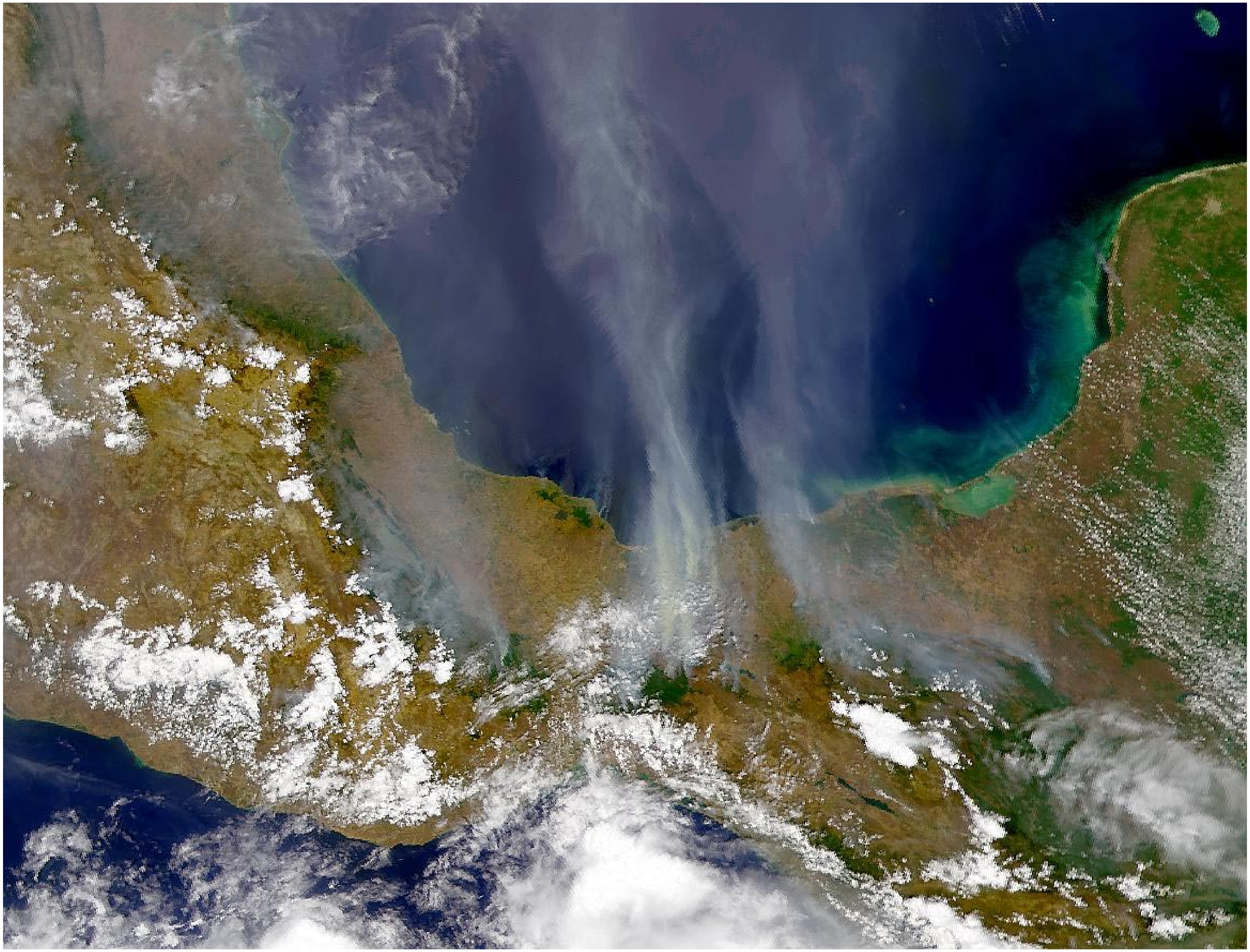
Photo credit: Berk Knighton

AEROSOL IN MEXICO CITY BASIN

Photo credit: Berk Knighton

Light scattering by aerosols decreases absorption of solar radiation.

AEROSOLS AS SEEN FROM SPACE

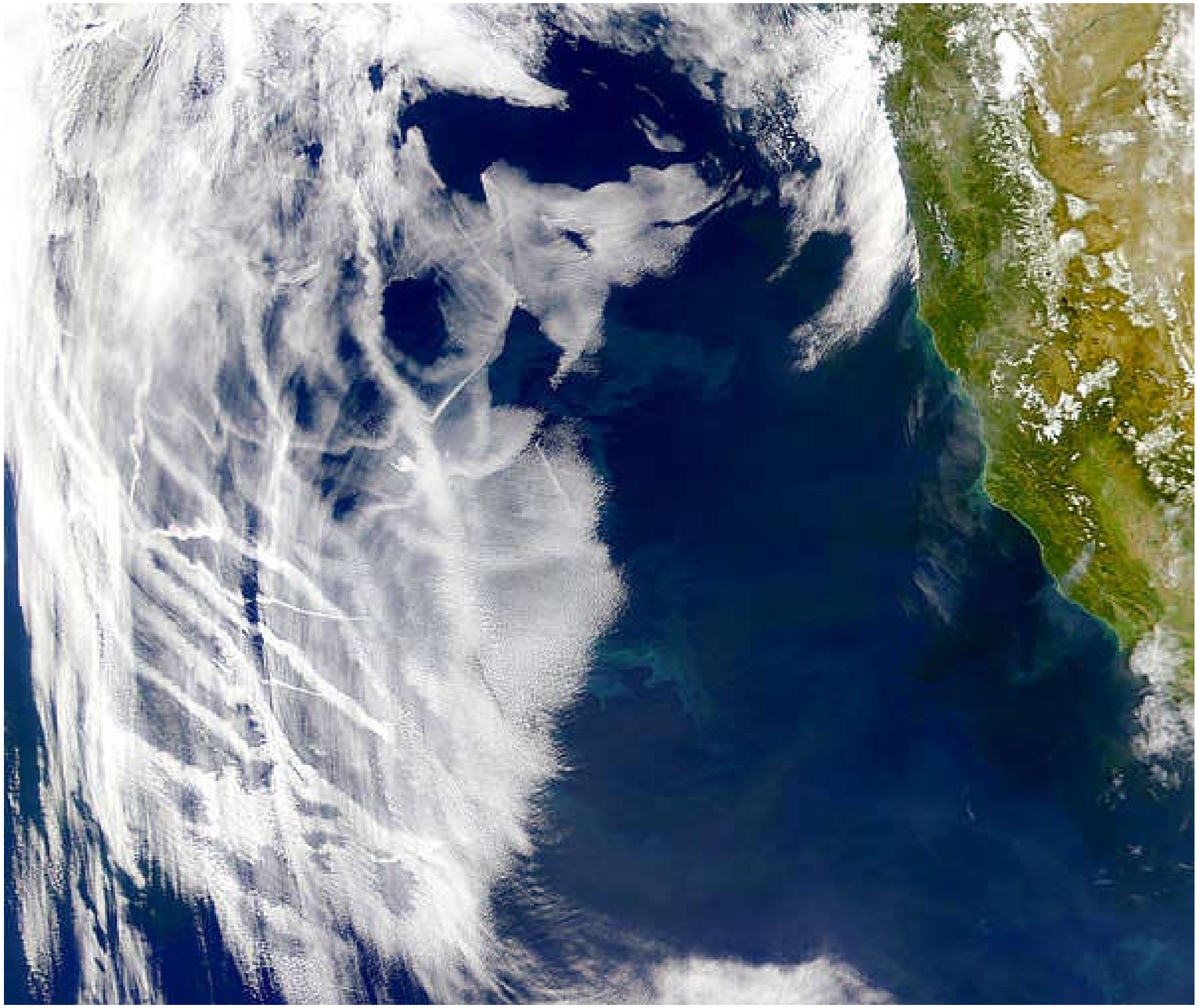


Credit: SeaWIFS

Fire plumes from southern Mexico transported north into Gulf of Mexico.

CLOUD BRIGHTENING BY SHIP TRACKS

Satellite photo off California coast

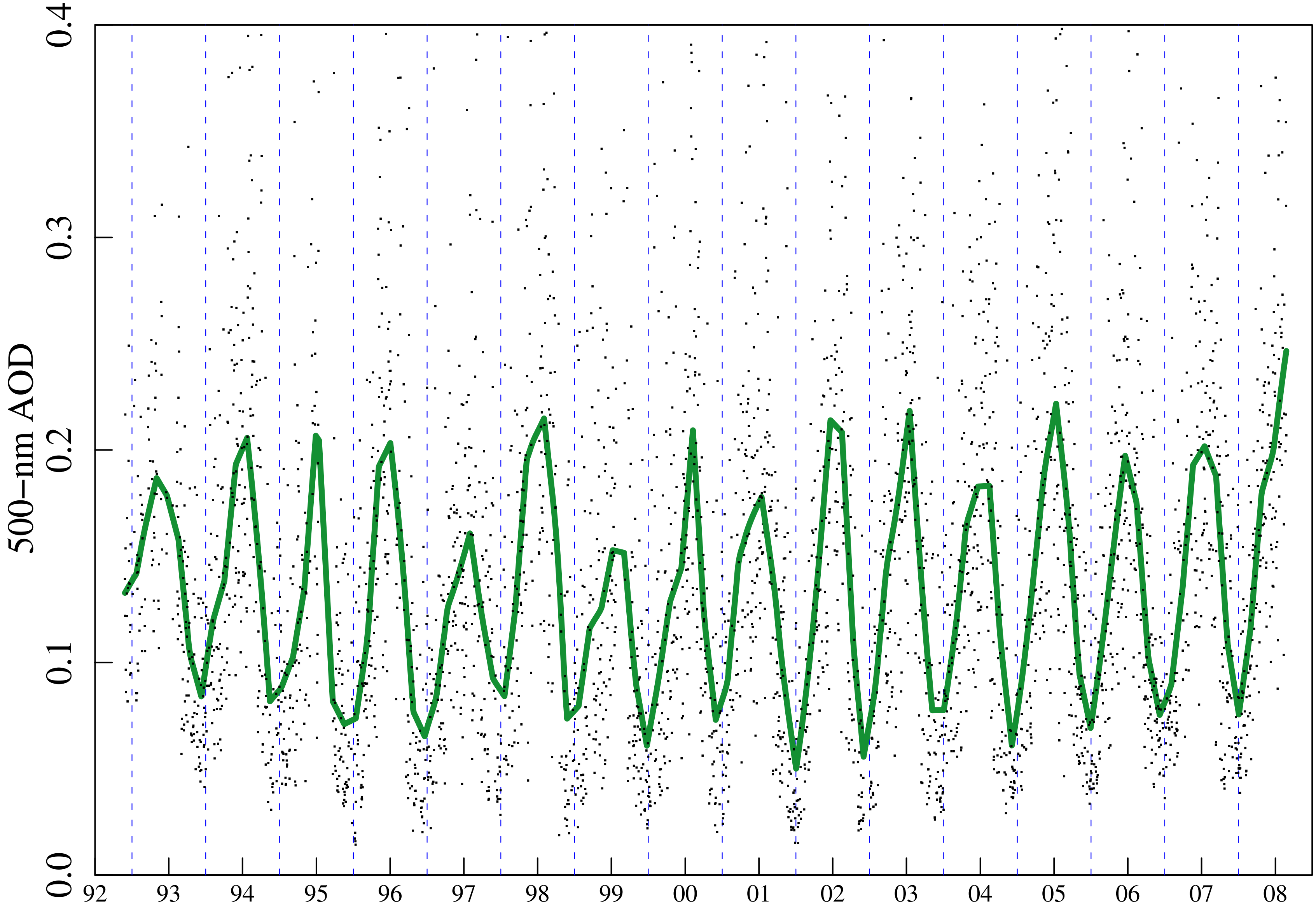


Credit: SeaWIFS

Aerosols from ship emissions enhance reflectivity of marine stratus.

AEROSOL OPTICAL DEPTH AT ARM SGP

Fifteen years of daily average 500 nm AOD in North Central Oklahoma

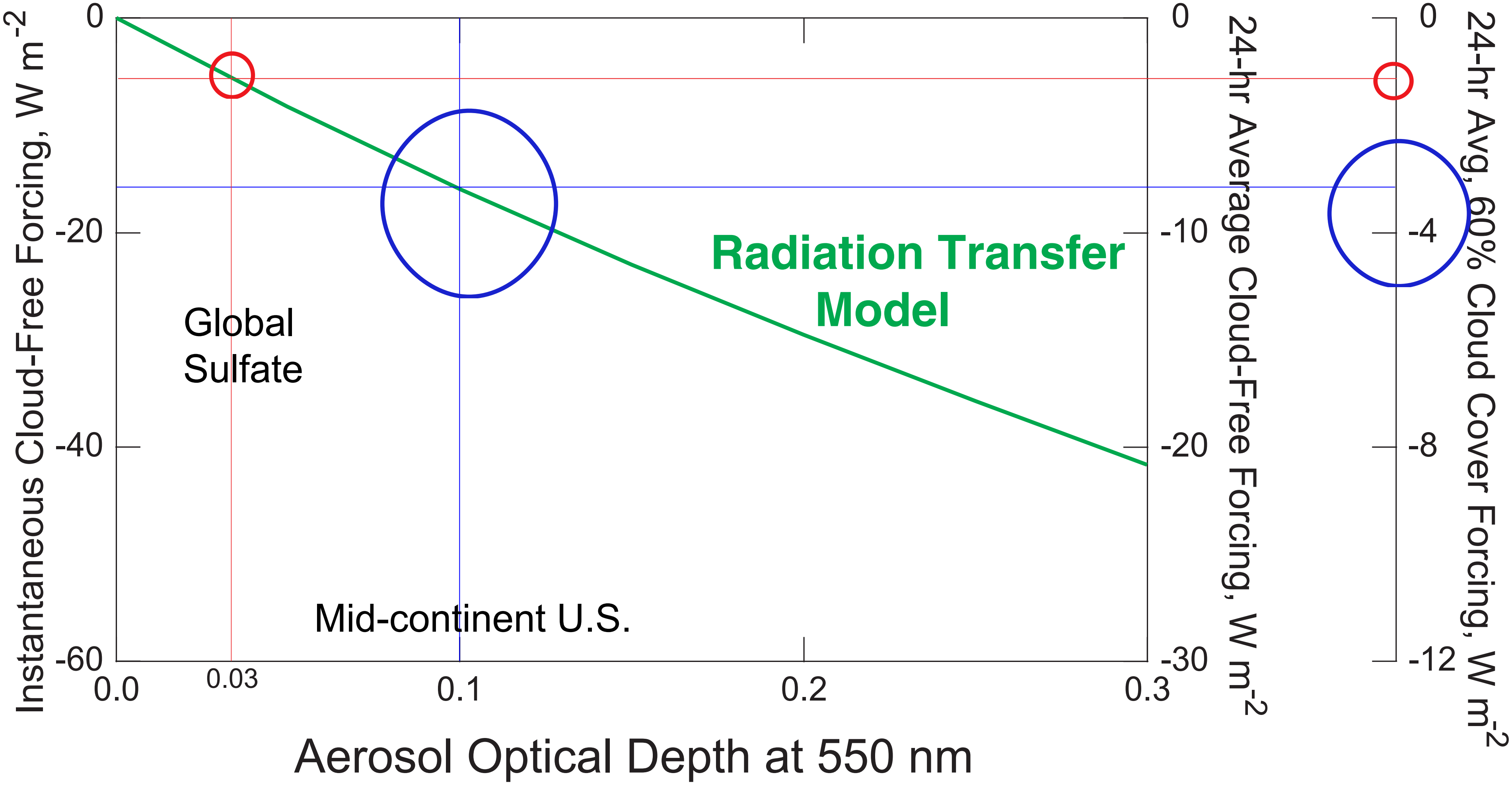


Michalsky, Denn, Flynn, Hodges, Kiedron, Koontz, Schlemmer, Schwartz, JGR, 2010

Green curve is LOWESS (locally weighted scatterplot smoothing) fit.

ESTIMATES OF AEROSOL DIRECT FORCING

By radiation transfer modeling

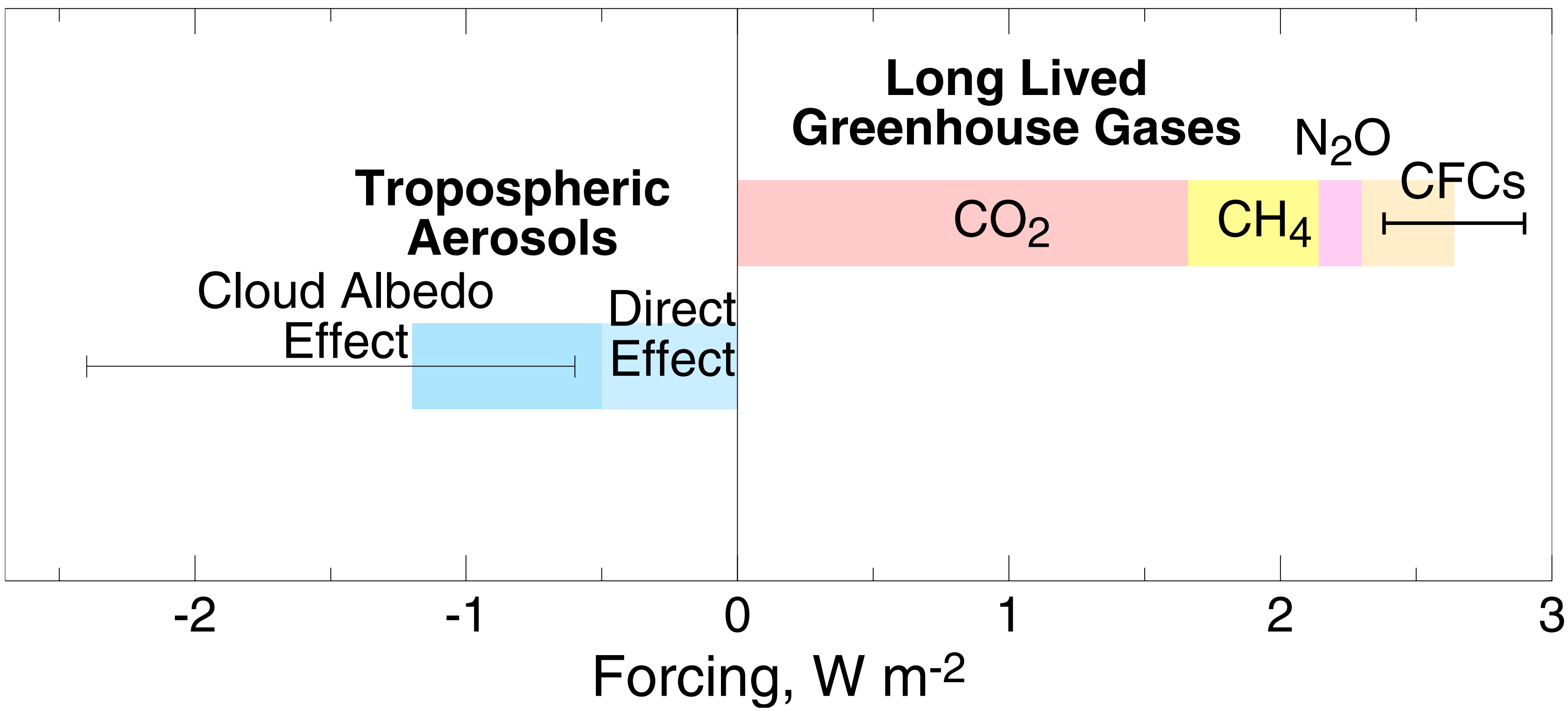


Global average sulfate optical thickness is 0.03: ***1 W m^{-2} cooling***.

In ***continental U. S.*** typical aerosol optical thickness is 0.1: ***3 W m^{-2} cooling***.

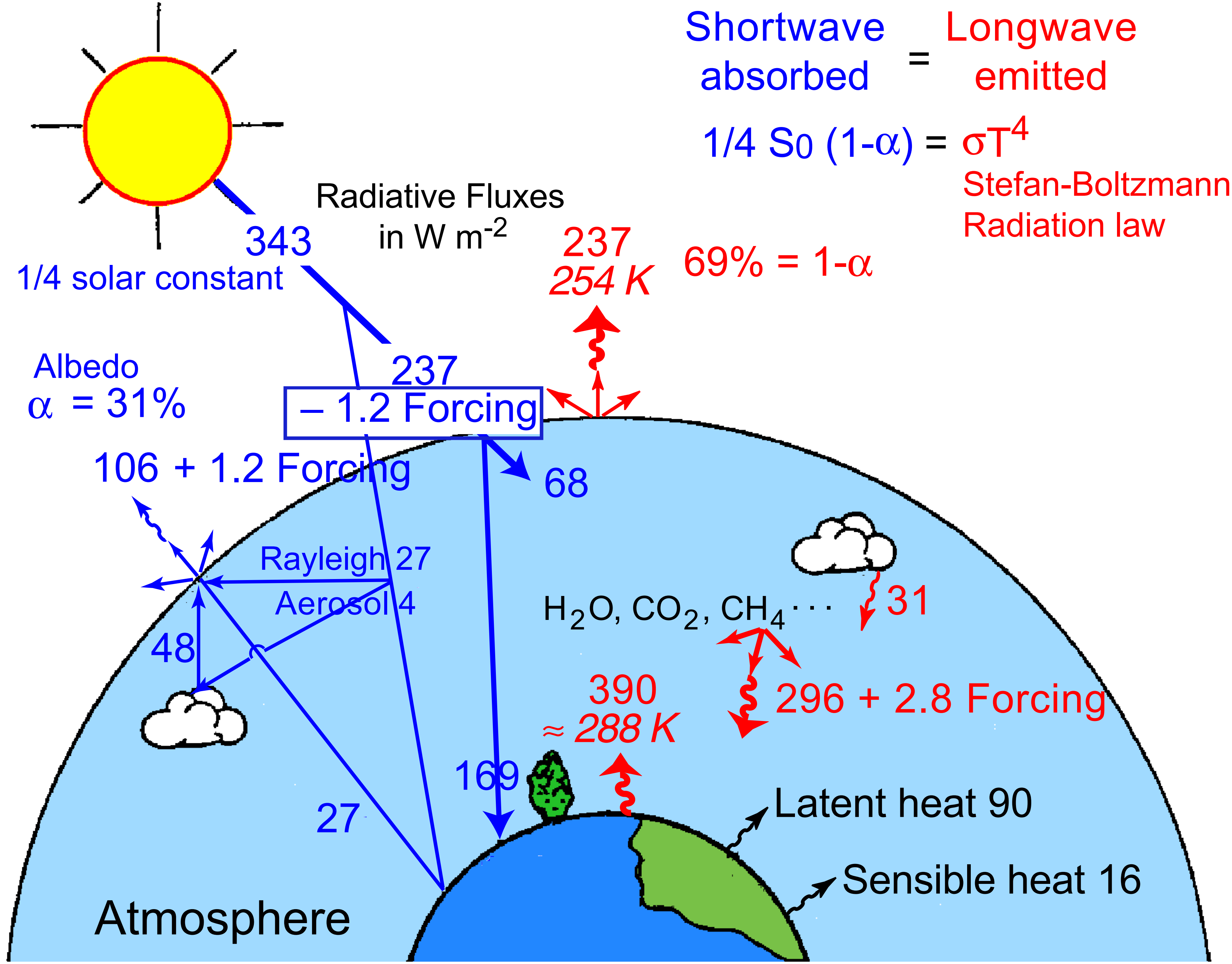
CLIMATE FORCINGS OVER THE INDUSTRIAL PERIOD

Extracted from IPCC AR4 (2007)



Aerosols exert a negative (cooling) forcing, opposite to greenhouse gases.

THE GREENHOUSE EFFECT AND EARTH'S RADIATION BUDGET



Modified from Schwartz, 1996; Ramanathan. 1987

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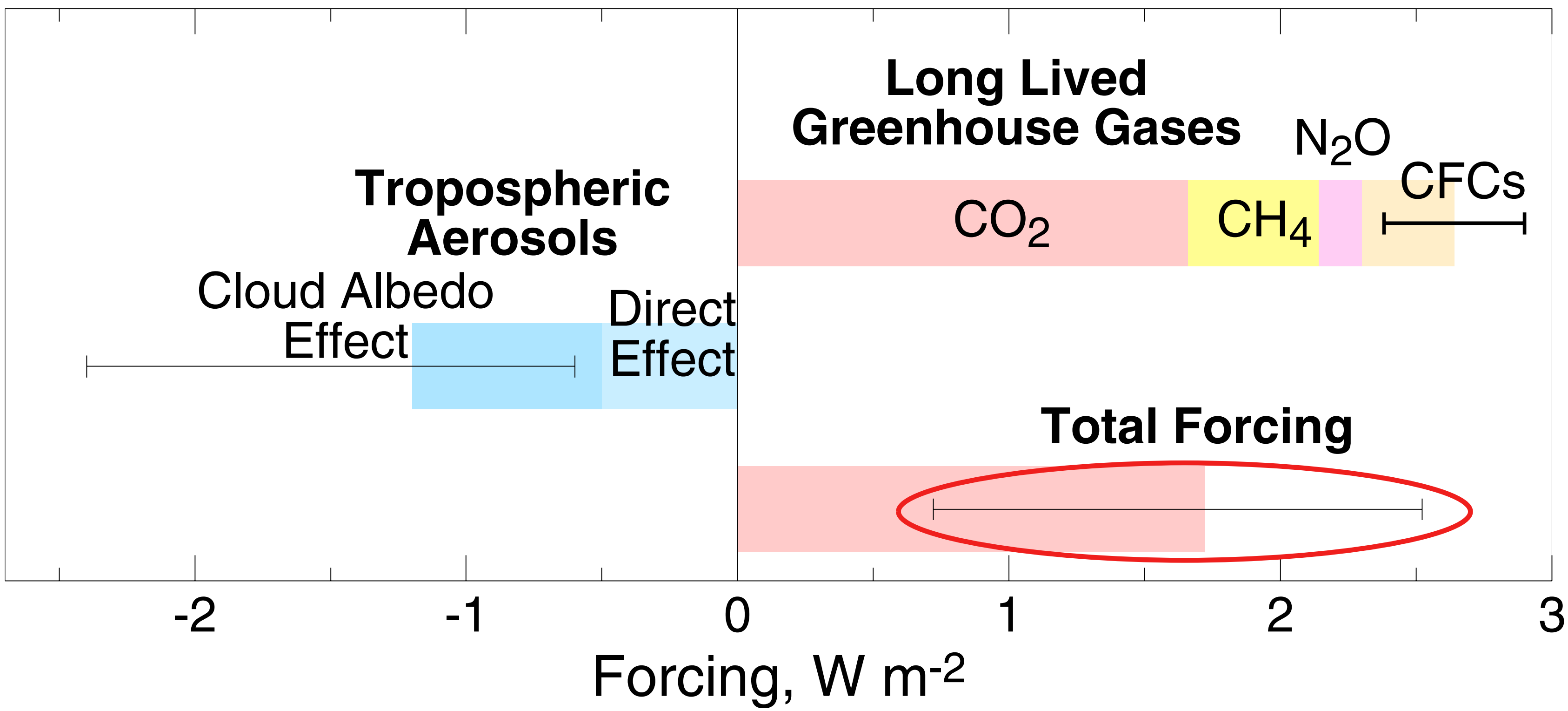
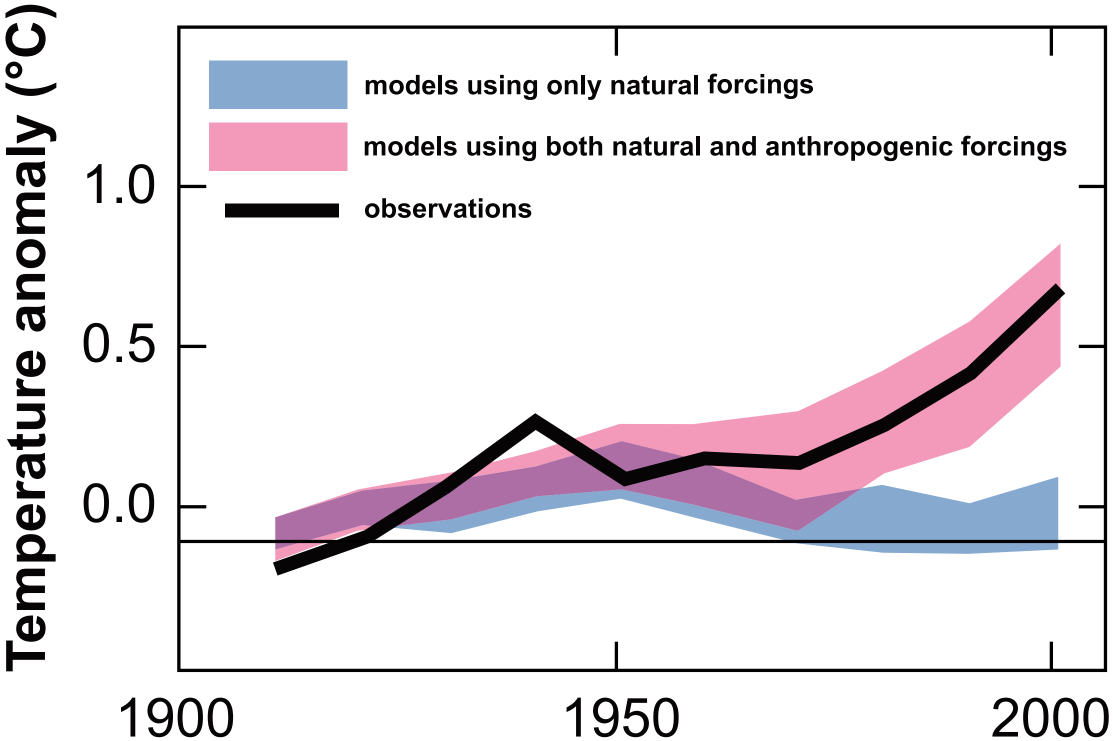


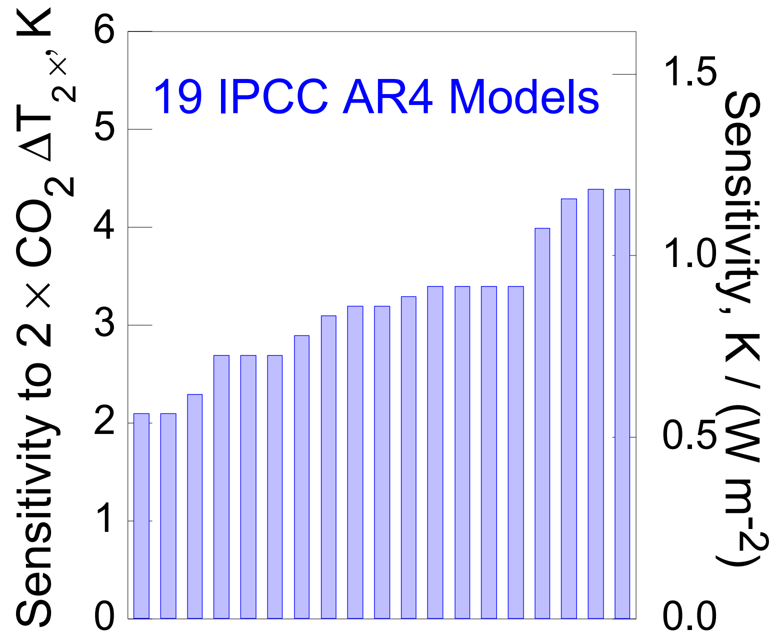
Aerosol forcing may offset much of the greenhouse gas forcing.

Uncertainty in total forcing is dominated by uncertainty in aerosol forcing.

OBSERVED AND MODELED WARMING

Ensemble of 58 model runs with 14 global climate models





“ Simulations that incorporate anthropogenic forcings, including increasing greenhouse gas concentrations and the effects of aerosols, and that also incorporate natural external forcings provide a ***consistent explanation of the observed temperature record***.

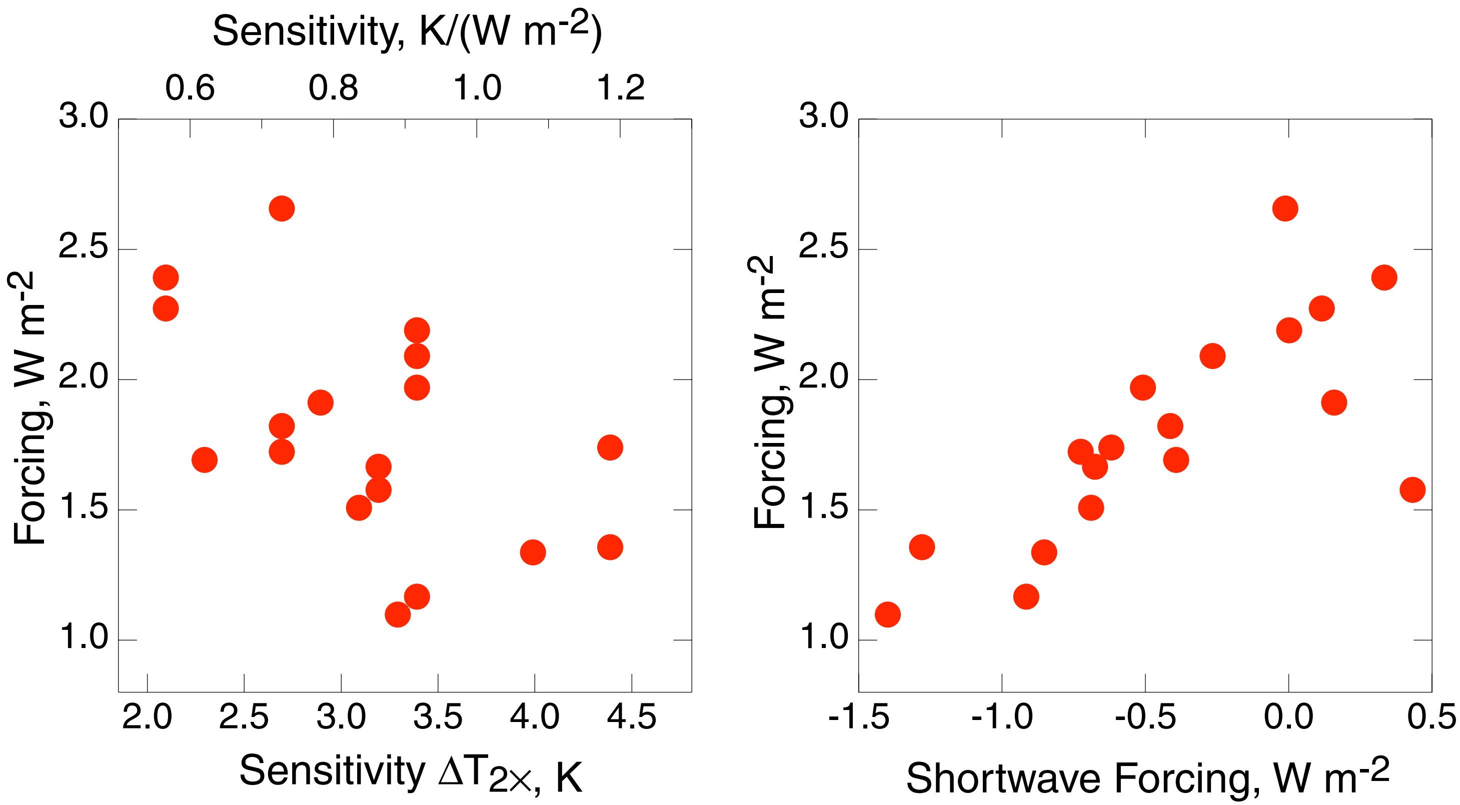
“ These simulations used models with ***different climate sensitivities, rates of ocean heat uptake and magnitudes and types of forcings***.

IPCC AR4, 2007

How can this be?

CORRELATION OF FORCING AND SENSITIVITY IN CLIMATE MODELS

18 IPCC 2007 climate models



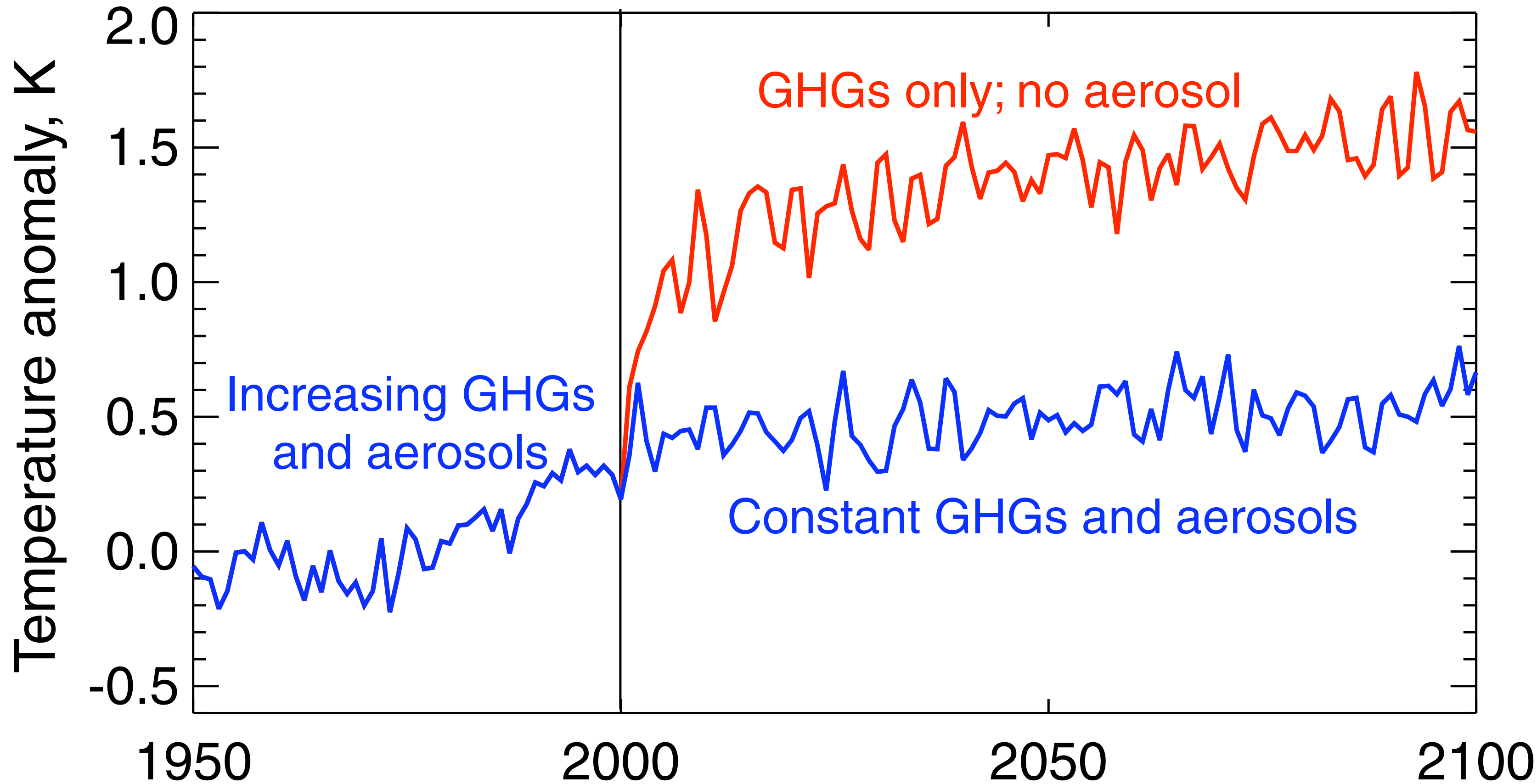
After Kiehl (2007); data from Forster and Taylor (2006)

To reproduce observed 20*th* century temperature increase, models with low sensitivity employ large forcing, and vice versa.

Variation in forcing is due mainly to variation in shortwave forcing, primarily aerosol forcing.

GLOBAL TEMPERATURE RESPONSE TO TURNING OFF AEROSOL EMISSIONS

Experiment with ECHAM-5 GCM



Modified from Brasseur and Roeckner, GRL, 2005

For constant GHGs and aerosols, temperature remains near year 2000 value.

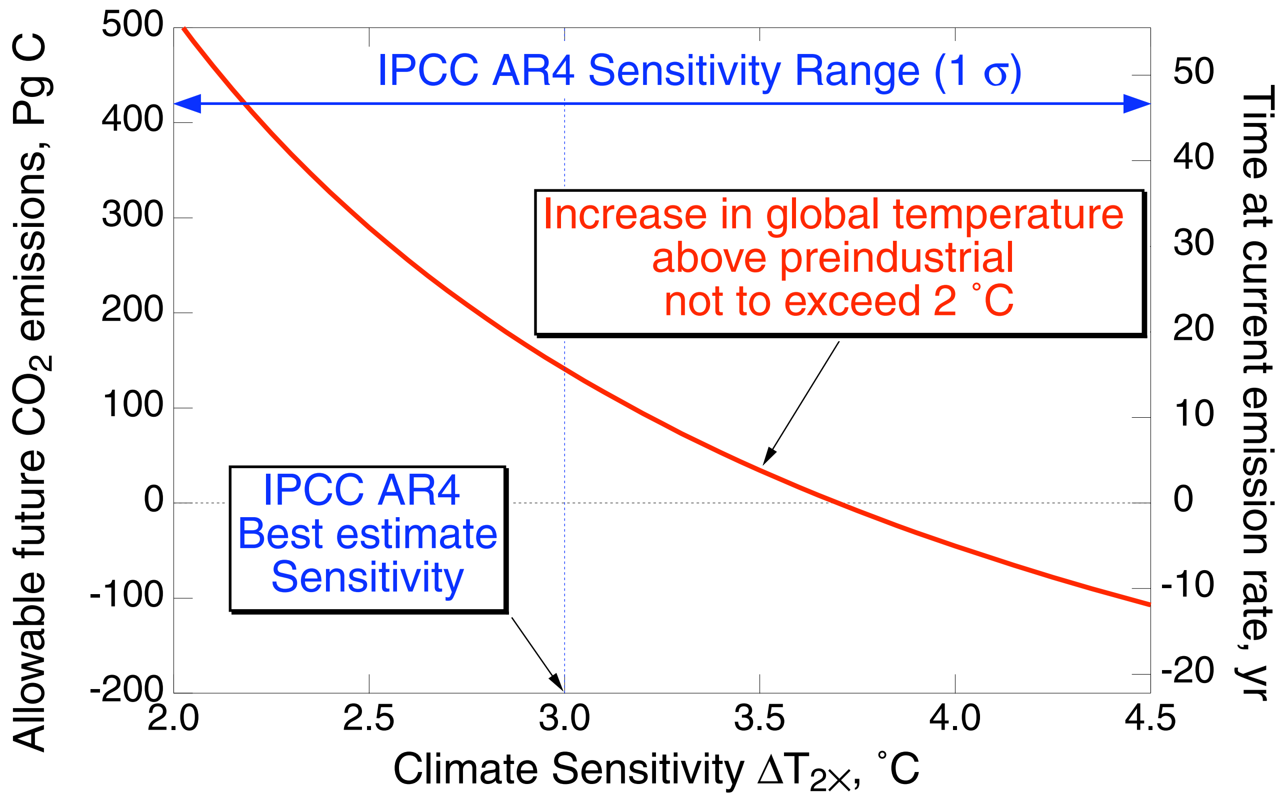
Without aerosol offset to GHG forcing temperature rapidly increases.

However the magnitude of the aerosol offset is unknown.

ALLOWABLE FUTURE CO_2 EMISSIONS

Such that commited increase in global mean temperature not exceed 2˚C

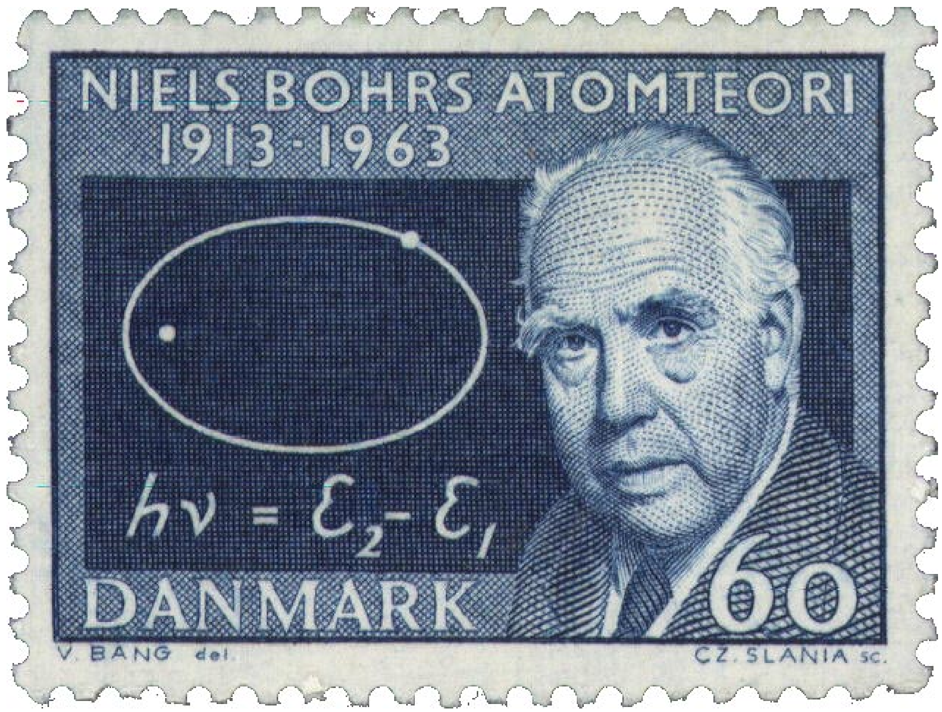
Greenhouse gas forcing only, with planetary heating rate 0.8 W m^{-2}



For IPCC best-estimate senstivity, only about 15 years more emissions at current rates.

At current emission rates, for IPCC sensitivity range, allowable emissions range from +60 years to –10 years.

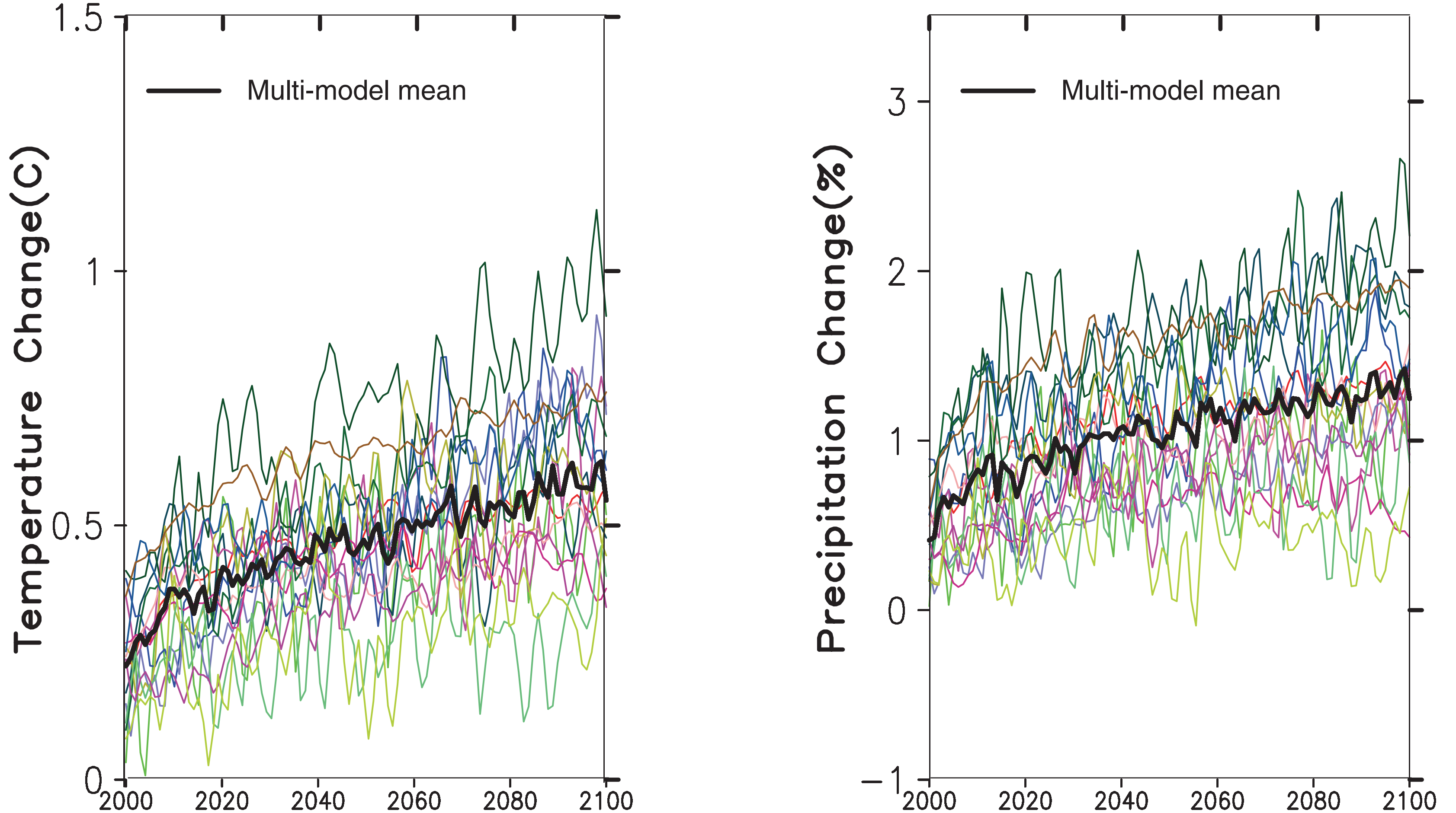
Prediction is difficult, especially about the future.



– Niels Bohr

TWENTY-FIRST CENTURY CLIMATE CHANGE

Change in ***global*** temperature and precipitation for fixed atmospheric composition, relative to 1980-1999, calculated with 16 GCMs



IPCC, 2007

Agreement that ***temperature and precipitation are expected to increase, even for no further change in atmospheric composition***.

OBSERVATIONALLY BASED PERTURBATION MODELING

Approach

Examine the consequences of a ***perturbation*** about an initial state.

Identify the processes that will be influenced by the perturbation.

Determine, ***by observation guided by theory***, the responses of the processes to the perturbation (partial derivatives).

Develop relatively simple models that characterize responses to perturbations.

Evaluate by suitable surrogates.

Strength

The perturbation is first order in the model, not a difference

Concerns

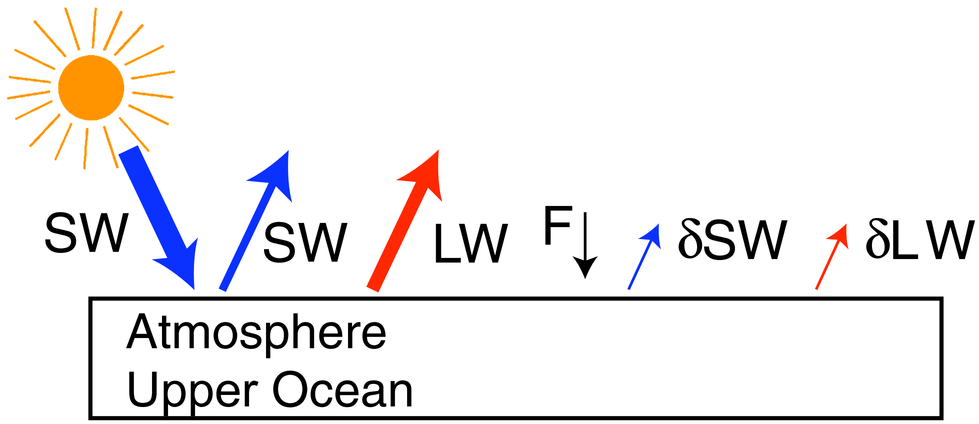
Correlation is not causality. Correlations can mislead.

The available span of variation in quantities of interest may not be sufficient to yield accurate predictive capability.

Limited number of predictive variables.

GLOBAL ENERGY BALANCE MODELS

Single compartment climate model



Energy conservation in the climate system:

$$\boxed{\frac{dH}{dt} \equiv N = Q - E}$$

H = planetary heat content;

N = net heating rate of planet;

Q = absorbed shortwave at TOA;

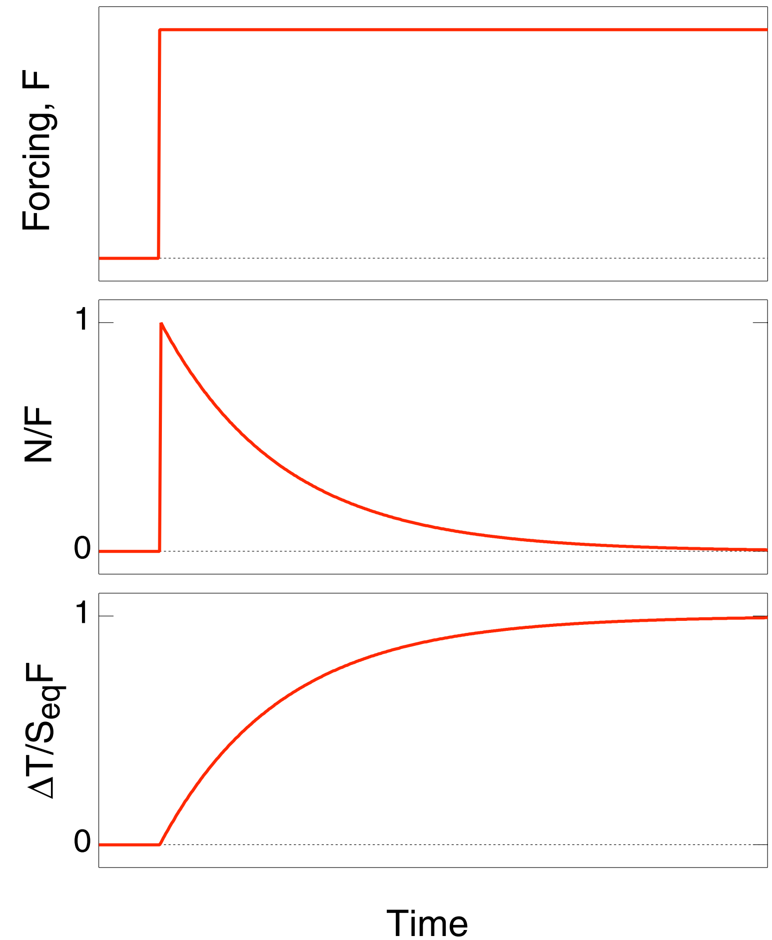
E = emitted longwave at TOA.

Unperturbed steady state (equilibrium) climate:

$$N = 0; \qquad Q_0 = E_0$$

Net heating rate with external forcing F applied:

$$\boxed{N(t) = Q(t) - E(t) + F(t)}$$



Initially after onset of forcing

$$Q = Q_0; \qquad E = E_0; \qquad N = F$$

Climate response to forcing

$$N(t) = F(t) + \frac{\partial(Q-E)}{\partial T}\Delta T(t)$$

$$N(t) = F(t) - \lambda\Delta T(t)$$

where $\lambda \equiv -\dfrac{\partial(Q-E)}{\partial T}$ is *climate response coefficient.*

λ is a geophysical property of Earth's climate system.

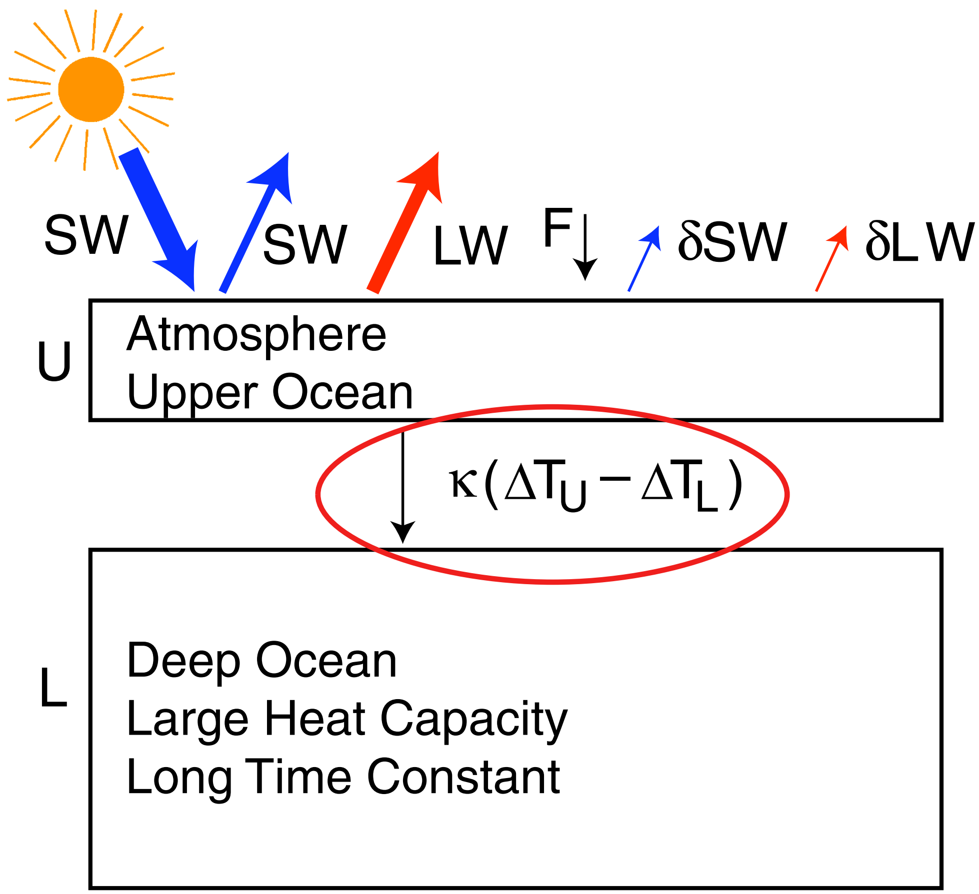
At new steady state (equilibrium) following application of constant forcing F

$$N = 0; \quad \lambda \Delta T = F; \quad \boxed{\Delta T = \lambda^{-1} F = S_{\mathrm{eq}} F}$$

S_{eq} = *equilibrium climate sensitivity* = λ^{-1}.

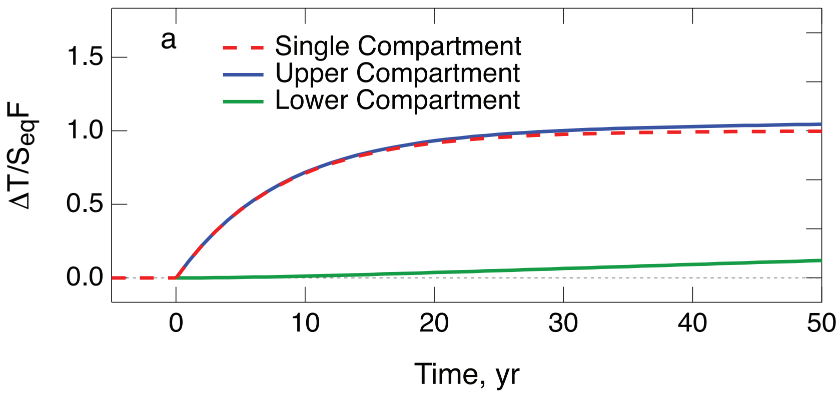
S_{eq} is a geophysical property of Earth’s climate system.

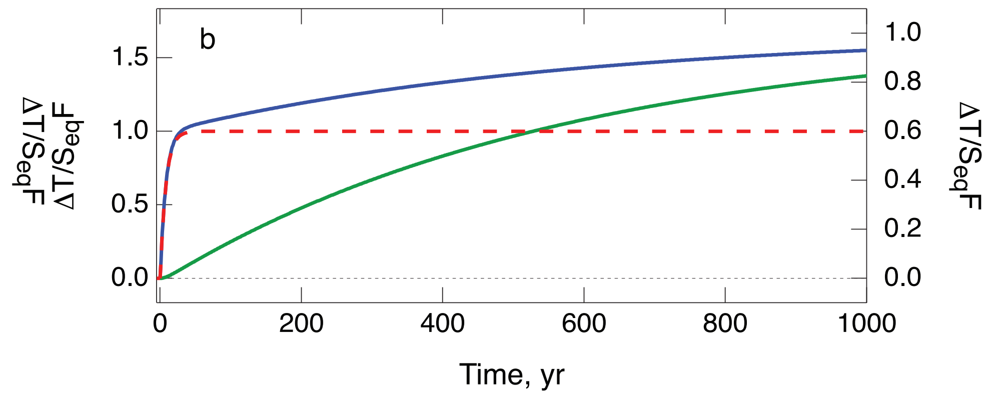
Two compartment climate model



TIME RESPONSE IN TWO-COMPARTMENT MODEL

Response to step-function forcing





Parameters:

	Single	Upper	Lower
Time Constant, yr	8	8	567
Heat Capacity, W yr m^{-2} K^{-1}		20	340
Sensitivity K(W m^{-2}) $^{-1}$	0.4	$S_{tr} = 0.4$	$S_{eq} = 0.67$

Heat exchange coefficient, $\kappa = 1$ W m^{-2} K^{-1}

One-compartment model is indistinguishable from two-compartment model on time scales of 50 years or more, but levels off to transient sensitivity.

PREDECESSORS TO THIS MODEL

Gregory,
Climate Dynamics,
2001

$$c d_{\mathrm{u}} \frac{\mathrm{d}T_{\mathrm{u}}}{\mathrm{d}t} = H - k(T_{\mathrm{u}} - T_{\mathrm{l}})$$

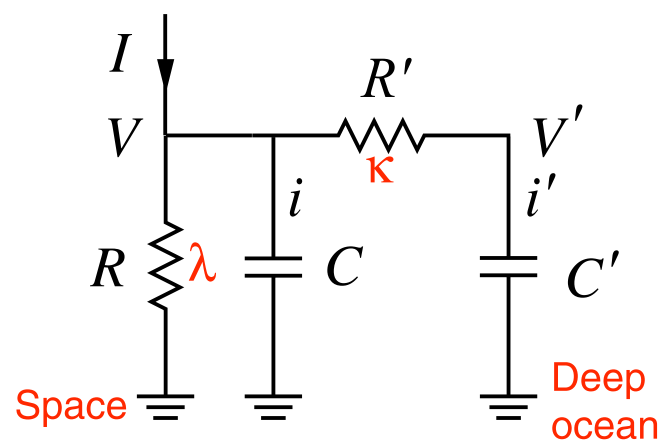
$$c d_{\mathrm{l}} \frac{\mathrm{d}T_{\mathrm{l}}}{\mathrm{d}t} = k(T_{\mathrm{u}} - T_{\mathrm{l}})$$

Held et al,
J. Climate, 2010

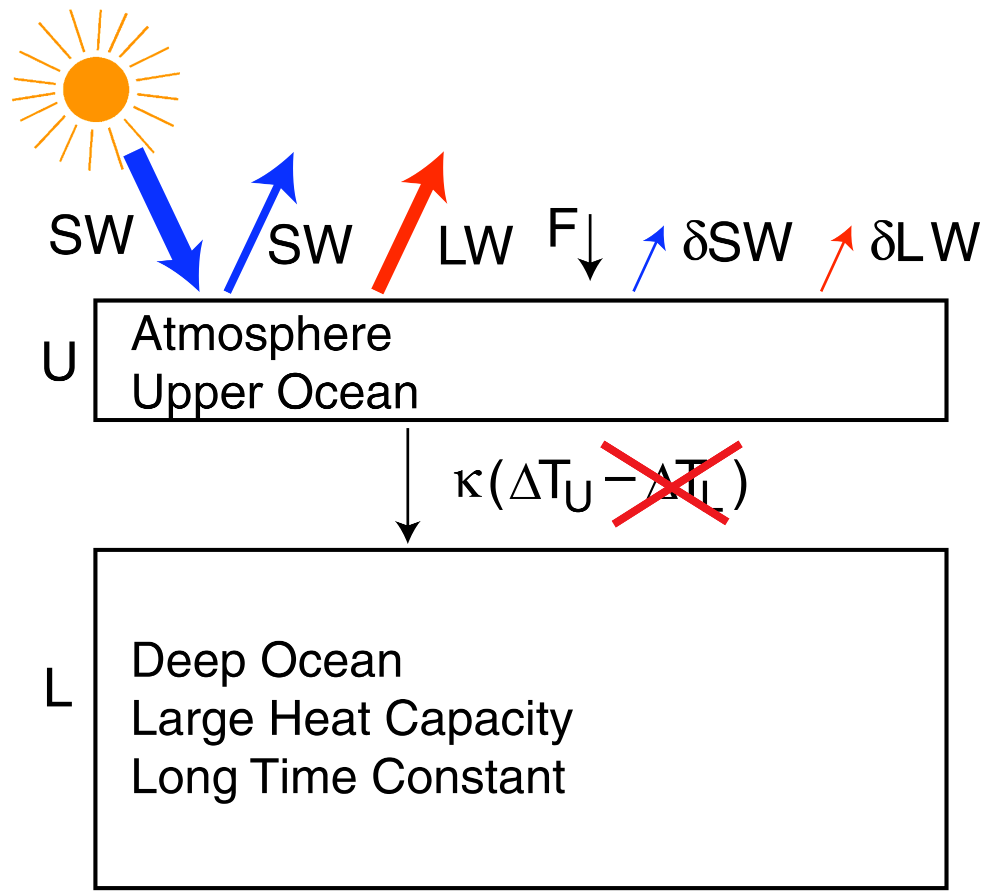
$$c_F \frac{dT}{dt} = \mathcal{F} - \beta T - \gamma(T - T_D)$$

$$c_D \frac{dT_D}{dt} = \gamma(T - T_D)$$

Schwartz,
JGR, 2008



Two compartment climate model



TRANSIENT CLIMATE SENSITIVITY

Hypothesis: Planetary heating rate proportional to ΔT

$$\boxed{N(t) = \kappa \Delta T(t)}$$

κ = *heat exchange coefficient*, a geophysical property of Earth's climate system.

$$N(t) = F(t) - \lambda \Delta T(t)$$

$$F(t) = (\kappa + \lambda)\Delta T(t); \quad \Delta T(t) = (\kappa + \lambda)^{-1} F(t) = S_{\mathrm{tr}} F(t)$$

S_{tr} = *transient climate sensitivity*, $S_{\mathrm{tr}} \equiv (\kappa + \lambda)^{-1}$, a geophysical property of Earth's climate system

Contrast equilibrium sensitivity, $S_{\mathrm{eq}} = \lambda^{-1}$

Response times in two-compartment model

$$\tau_{\mathrm{s}} = \frac{C_{\mathrm{U}}}{\kappa + \lambda} \qquad \tau_{\mathrm{l}} = C_{\mathrm{L}}\left(\frac{1}{\lambda} + \frac{1}{\kappa}\right)$$

Obtained from eigenvalues, to first order in $C_{\mathrm{U}} / C_{\mathrm{L}}$.

τ_{s} and τ_{l} are geophysical properties of Earth's climate system.

C_{L} is heat capacity of deep ocean (average depth 3.8 km; fractional area 0.71).

Other quantities to be determined empirically.

Determination of transient sensitivity

Recall S_{tr} = *transient climate sensitivity*, $S_{\mathrm{tr}} \equiv (\kappa + \lambda)^{-1}$

$$\tau_{\mathrm{s}} = \frac{C_{\mathrm{U}}}{\kappa + \lambda} \qquad \text{Hence, } \boxed{S_{\mathrm{tr}} = \frac{\tau_{\mathrm{s}}}{C_{\mathrm{U}}}}$$

One equation in three unknowns!

Approach: Determine τ_{s} and C_{U} from observations.

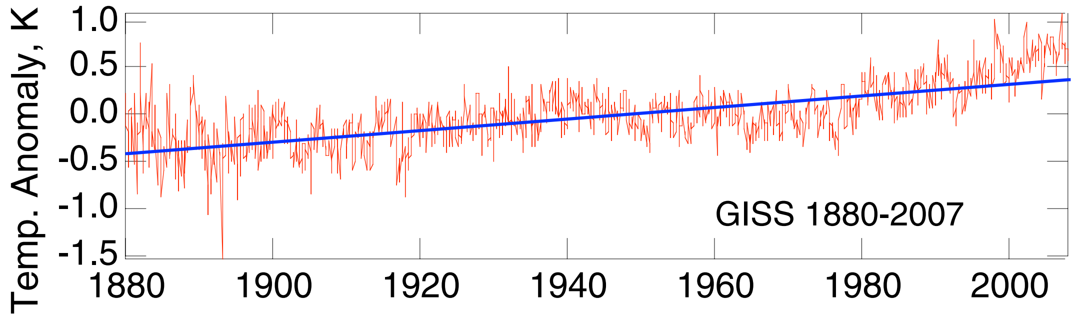
Determination of equilibrium sensitivity

$$S_{\mathrm{eq}} = \lambda^{-1} = \left(S_{\mathrm{tr}}^{-1} - \kappa\right)^{-1}$$

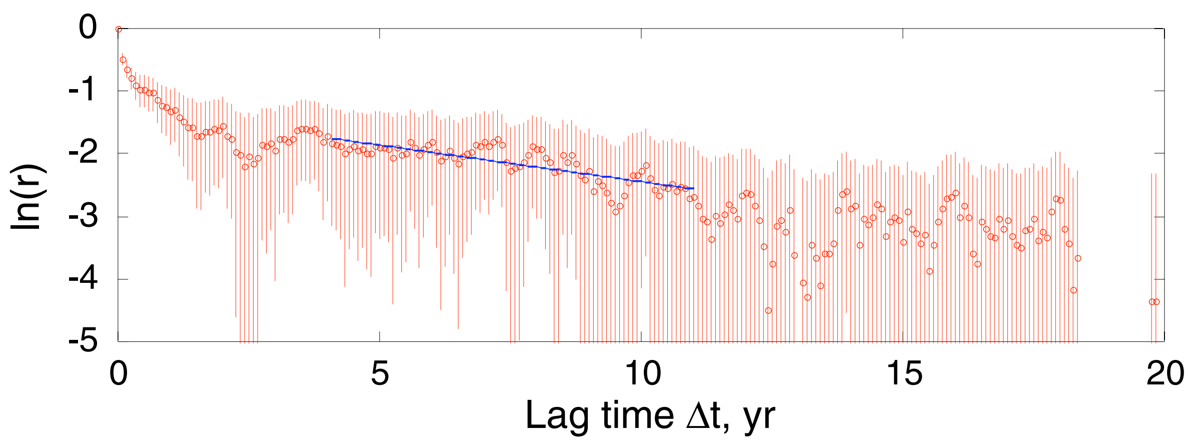
Approach: Determine κ from observations.

TIME CONSTANT OF EARTH'S CLIMATE SYSTEM
Determination from autocorrelation of time series

Input: Monthly global-mean surface temperature anomaly T_s



Calculate correlation coefficient of detrended time series with itself, lagged by Δt, $r(\Delta t)$.



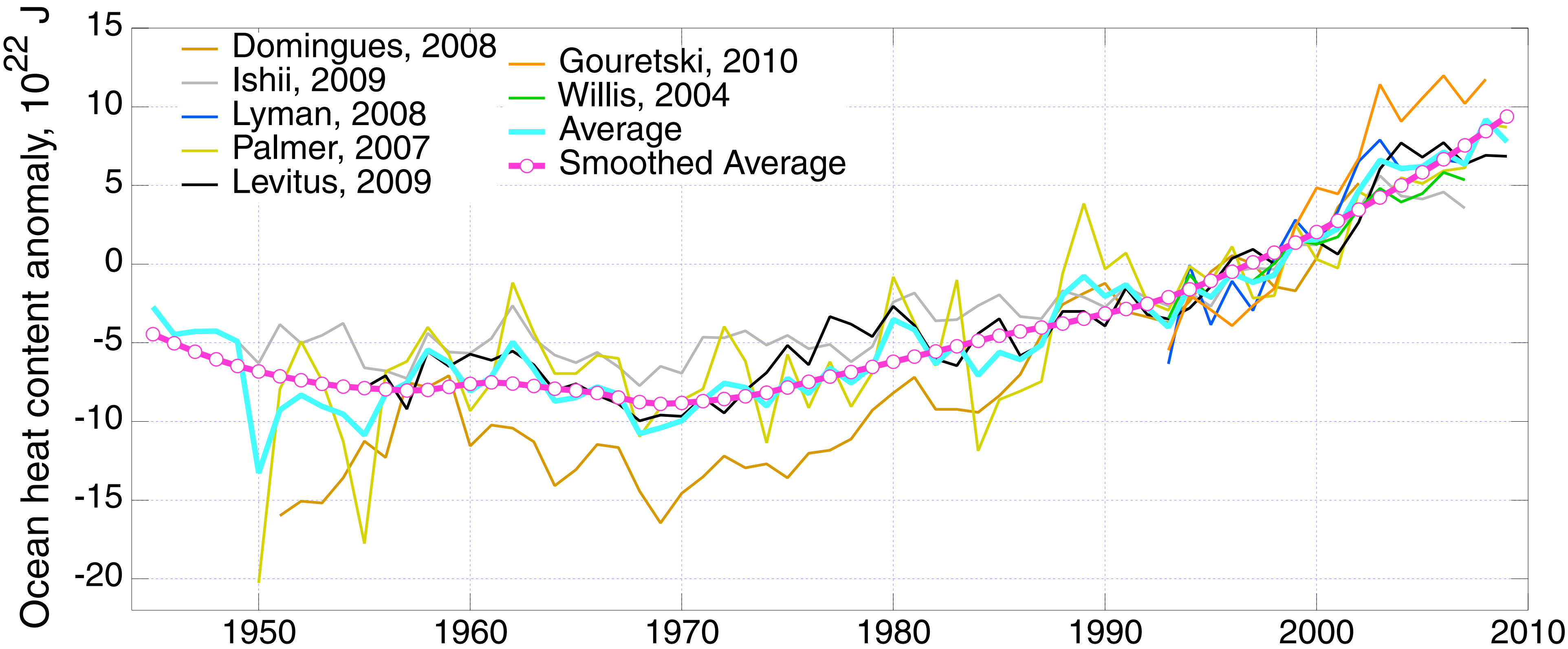
$r(\Delta t) = e^{-\Delta t/\tau}$, whence $\tau(\Delta T) = -\Delta T \,/\ln r(\Delta T) = 8.6 \pm 0.7$ yr.

EMPIRICAL DETERMINATION OF UPPER COMPARTMENT HEAT CAPACITY

Hypothesis: Planetary heat content increases linearly with surface temperature ΔT.

Plot $H(t)$ vs $\Delta T(t)$; determine C_{U} as slope.

Heat content of global ocean



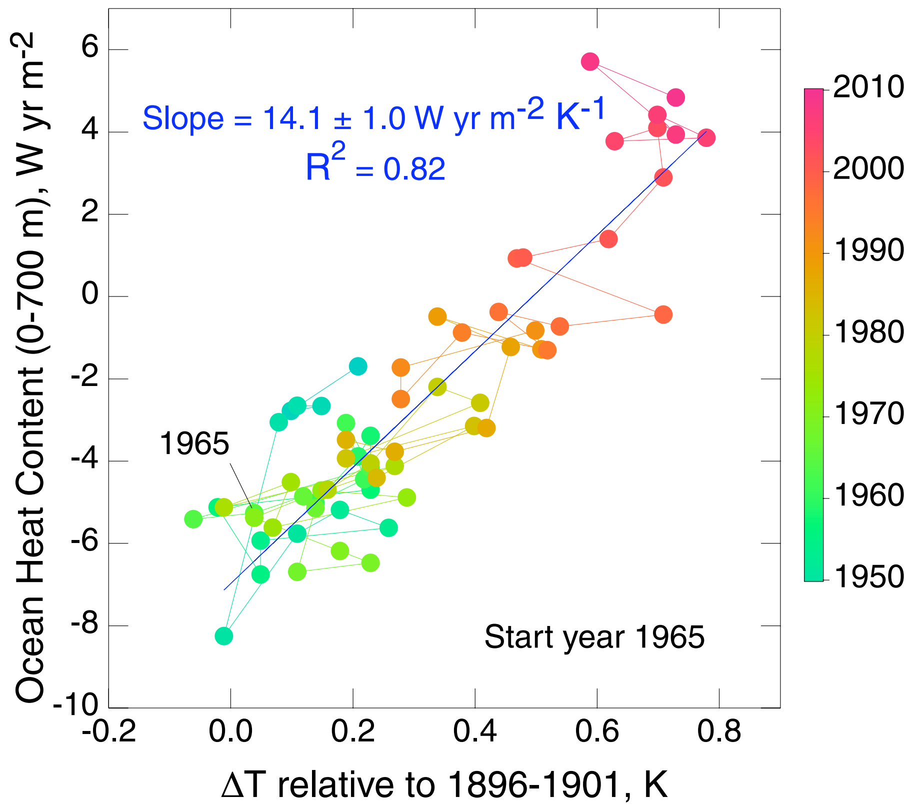
Heat content is from XBT soundings, later Argo robotic buoys.

Uncertainties from representativeness, techniques ...

Smoothed curve is LOWESS fit.

Monotonic increase since about 1970.

World ocean heat content vs temperature anomaly



Heat content varies linearly with temperature anomaly.

Heat capacity determined as slope, accounting for additional heat sinks (deep ocean, air, land, ice melting).

Upper compartment heat capacity $C_U = 21.8 \pm 2.1$ W yr m^{-2} K^{-1} (1 σ, based on fit, not systematic errors); equivalent to 170 m of seawater, globally.

EMPIRICAL DETERMINATION OF TRANSIENT CLIMATE SENSITIVITY

$$\boxed{S_{\mathrm{tr}} = \frac{\tau_{\mathrm{s}}}{C_{\mathrm{U}}}}$$

$\tau_{\mathrm{s}} = 8.6 \pm 0.7$ yr

$C_{\mathrm{U}} = 21.8 \pm 2.1$ W yr m^{-2}

Hence $S_{\mathrm{tr}} = 0.39 \pm 0.05$ K / (W m^{-2})

$\Delta T_{2\times,\mathrm{tr}} = 1.5 \pm 0.2$ K

EMPIRICAL DETERMINATION OF HEAT EXCHANGE COEFFICIENT

Hypothesis: Planetary heating rate proportional to ΔT

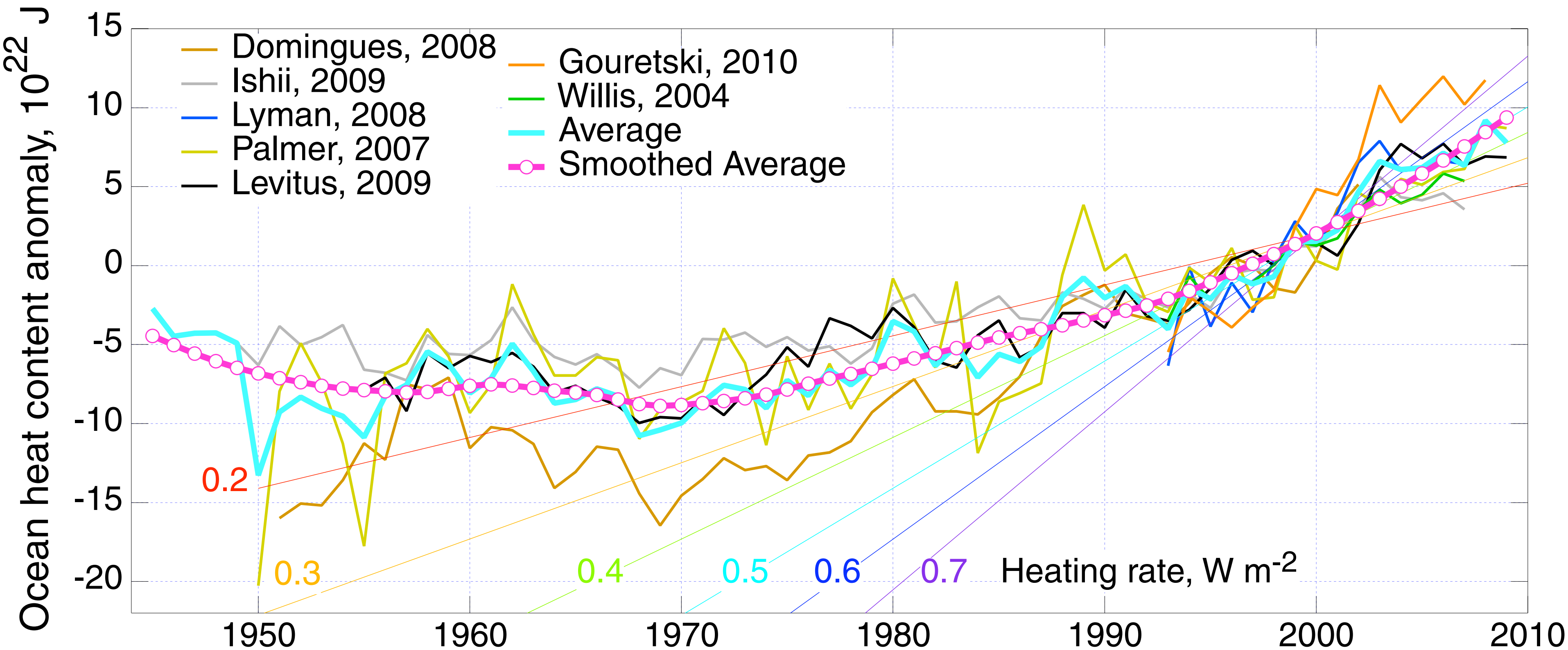
$$N(t) = \kappa \Delta T(t)$$

$\kappa = \textit{heat exchange coefficient}.$

Plot $N(t)$ vs $\Delta T(t)$; determine κ as slope (with zero origin).

κ is a geophysical property of Earth's climate system.

Heat content of global ocean



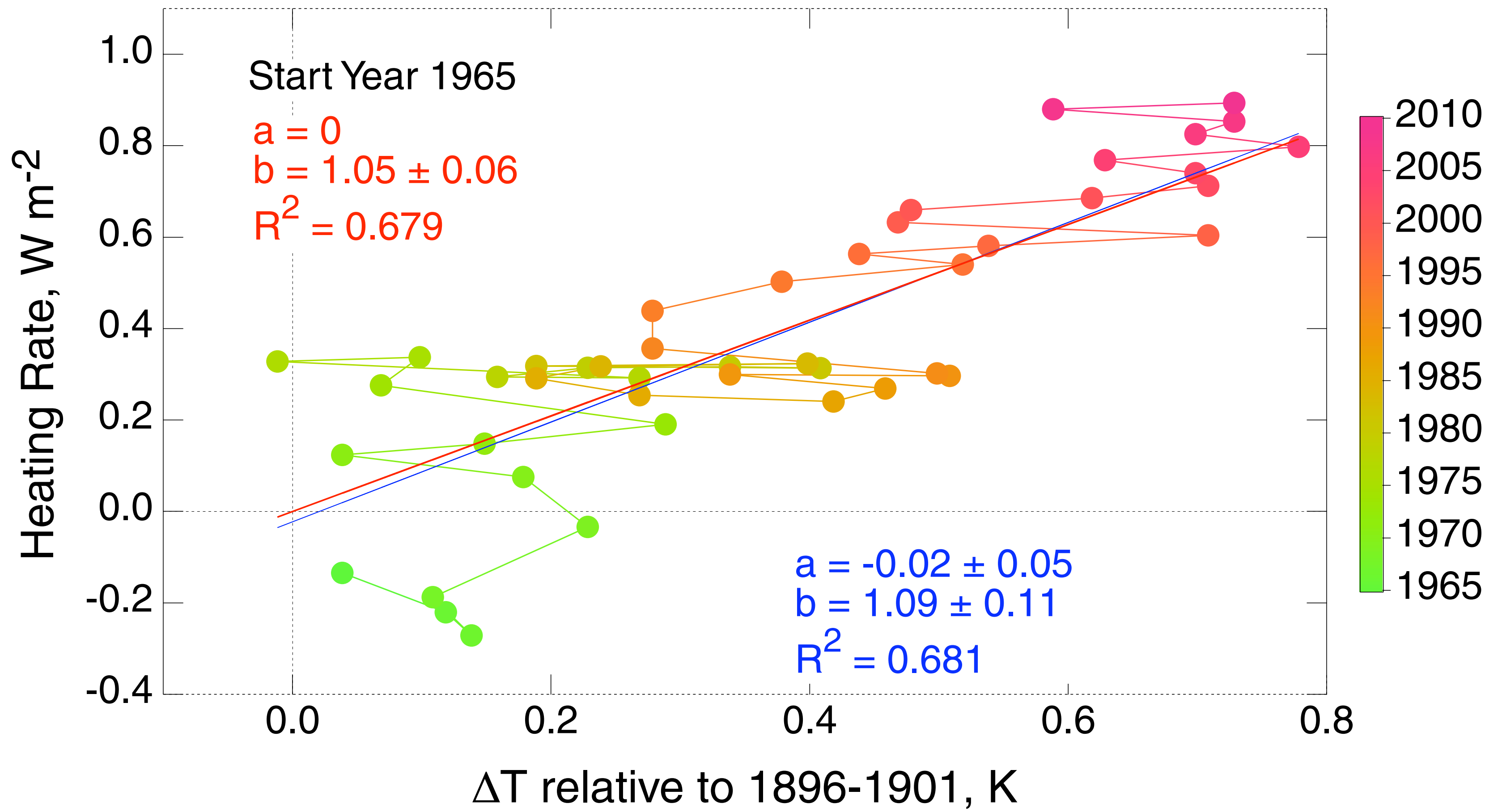
Heat content is from XBT soundings, later Argo robotic buoys.

Uncertainties from representativeness, techniques ...

Smoothed curve is LOWESS fit.

Monotonic increase since about 1970.

Global heating rate vs temperature anomaly



Heating rate (time derivative of ocean heat content) is ***linearly proportional*** to temperature anomaly.

$\boxed{\text{Heat exchange coefficient } \kappa = 1.05 \pm 0.06 \text{ W m}^{-2}\text{ K}^{-1}}$
(1σ, based on fit, not systematic errors).

EMPIRICAL DETERMINATION OF EQUILIBRIUM CLIMATE SENSITIVITY

Recall S_{tr} = *transient climate sensitivity*, $S_{\text{tr}} \equiv (\kappa + \lambda)^{-1}$

$$S_{\text{eq}} = \lambda^{-1} = \left(S_{\text{tr}}^{-1} - \kappa\right)^{-1}$$

$S_{\text{tr}} = 0.39 \pm 0.05$ K / (W m^{-2})

Heat exchange coefficient $\kappa = 1.06 \pm 0.05$ W m^{-2} K^{-1}

Hence *equilibrium climate sensitivity*
$S_{\text{eq}} = 0.68 \pm 0.09$ K / (W m^{-2})

CO_2 doubling temperature $\Delta T_{2\times,\text{eq}} = 2.5 \pm 0.3$ K

Remarkably close to central value of IPCC AR4 assessment: 3K, range 2 – 4.5 K.

DETERMINATION OF TWENTIETH CENTURY FORCING

Observed increase in temperature is proportional to forcing by the *transient climate sensitivity*, S_{tr}

$$\boxed{\Delta T_{obs}(t) = S_{tr} F(t)}$$

Hence

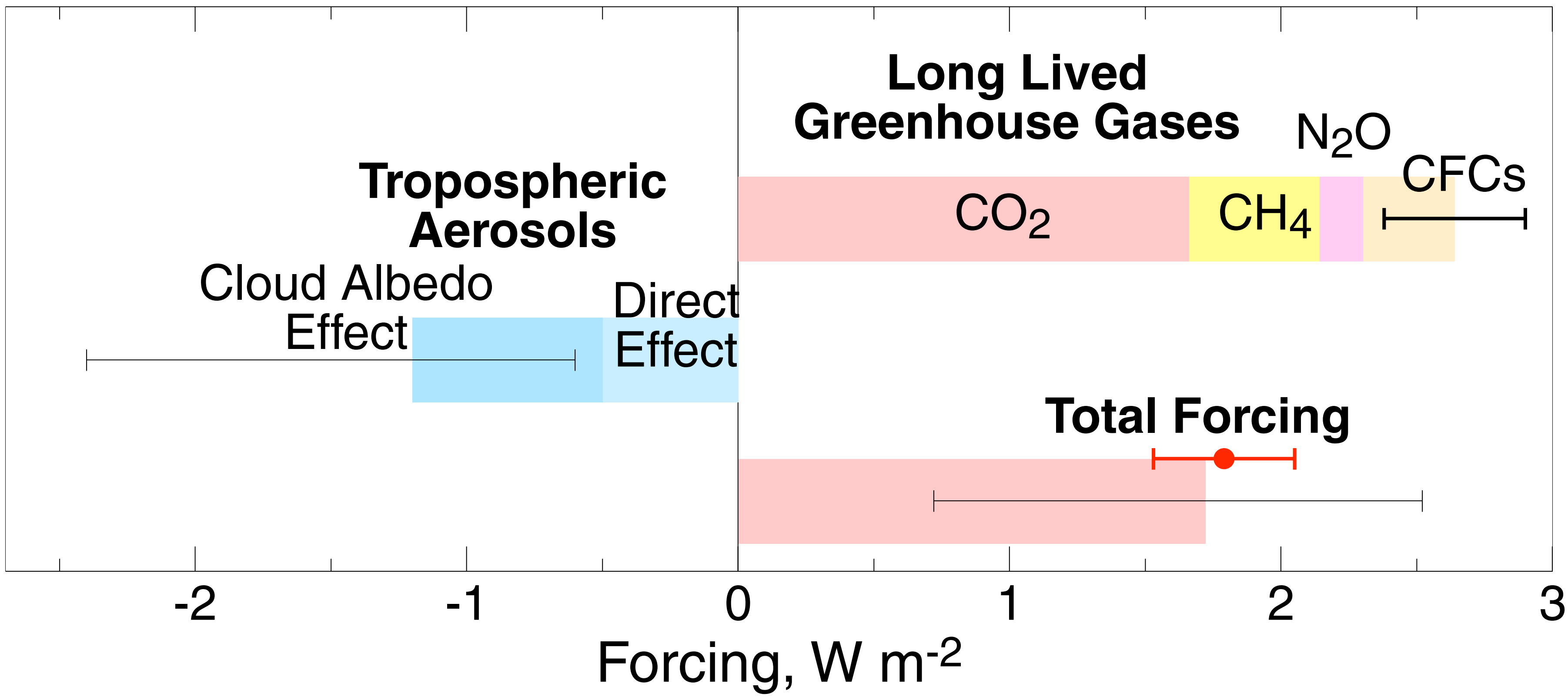
$$\boxed{F(t) = \frac{\Delta T_{obs}(t)}{S_{tr}}}$$

For $S_{tr} = 0.39 \pm 0.05$ K / (W m^{-2})

$\Delta T_{1900\text{-}2005} = 0.71 \pm 0.05$ K

$F_{1900\text{-}2005} = 1.79 \pm 0.26$ W m^{-2}

Climate forcing (1900 – 2005)



Twentieth century forcing is also ***remarkably close to IPCC central estimate*** (well within 1 σ).

GEOPHYSICAL QUANTITIES DETERMINED IN THIS STUDY

Quantity	Unit	Value	σ
C_U	W yr m^{-2} K^{-1}	21.8	2.1
C_L	W yr m^{-2} K^{-1}	340	
τ_s	yr	8.6	0.7
τ_l	yr	550	
κ	W m^{-2} K^{-1}	1.05	0.06
λ	W m^{-2} K^{-1}	1.5	0.2
S_{tr}	K/(W m^{-2})	0.39	0.05
$\Delta T_{2\times,\ tr}$	K	1.5	0.2
S_{eq}	K/(W m^{-2})	0.68	0.09
$\Delta T_{2\times,\ eq}$	K	2.5	0.3

SUMMARY & CONCLUSIONS (1)

Key questions about climate change are not yet answered with accuracy sufficient for important decisions on climate policy.

First principles climate modeling does a remarkably good job in representing Earth's climate system, but has not yet yielded the assessment of the consequences of small perturbations in radiative fluxes to needed accuracy.

Global energy-balance models ***use observations to determine key "ecological" properties of Earth's climate system***: heat capacities, heating rate, and time constants of response to perturbations.

These models thus afford the possibility of accurate determination of the transient and equilibrium sensitivities of the climate system.

SUMMARY & CONCLUSIONS (2)

For a two-compartment model the ***time constants*** are about 9 years and 500 years, pertinent to the transient and equilibrium sensitivities, respectively.

The rate of planetary heat uptake is found to be proportional to the increase in global temperature relative to the beginning of the twentieth century with ***heat transfer coefficient*** $\kappa = 1.05 \pm 0.06$ W m^{-2} K^{-1} (1 σ).

Earth's present ***energy imbalance*** is 0.80 ± 0.05 W m^{-2}.

The two-compartment model suggests that Earth's ***transient climate sensitivity***, expressed as a CO_2 doubling temperature is 1.5 ± 0.2 K. The ***equilibrium sensitivity*** 2.5 ± 0.3 K is ***close to IPCC central estimate***.

SUMMARY & CONCLUSIONS (3)

Total forcing over the twentieth century (to 2005) is estimated as 1.8 ± 0.3 W m^{-2}, indicative of ***aerosol offset*** of 0.8 W m^{-2}.

For transient sensitivity, present GHG forcing of 2.8 W m^{-2} implies ***committed warming*** of 1.1 K; for this forcing indefinitely sustained, this committed GHG warming would increase to 1.9 K.

The "ecological" approach to the study of climate change yields key properties of Earth's climate system and would appear to be very useful in the study of climate change.

Would I "bet the ranch" on this analysis? *NO!*